

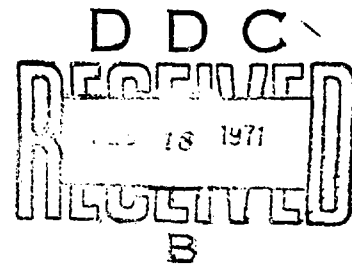
AFAPL-TR-70-65

**EFFECTS OF FUEL SLOSH AND VIBRATION ON
THE FLAMMABILITY HAZARDS OF
HYDROCARBON TURBINE FUELS WITHIN
AIRCRAFT FUEL TANKS**

*EDWIN E. OTT
CAPTAIN, USAF*

TECHNICAL REPORT AFAPL-TR-70-65

NOVEMBER 1970



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FOREWORD

This report was prepared by the Fire Protection Branch of the Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, with Captain Edwin E. Ott as the project engineer. The work reported herein was done under Project 3048, "Fuels, Lubrication, and Hazards," Task 304807, "Aerospace Vehicle Hazard Protection."

This report covers research accomplished in-house from 1 September 1969 through 30 April 1970 and was submitted by the author 1 September 1970.

The author appreciates the assistance received from other personnel of the Air Force Aero Propulsion Laboratory and other organizations at Wright-Patterson Air Force Base. Special thanks are given to the following in the AF Aero Propulsion Laboratory: Messrs H. Jones and J. Walick for setup, maintenance, and conduct of equipment and testing and to Mrs. A. Brenner and Mr. R. Lillie for aid in experiment design and data reduction.

This technical report has been reviewed and is approved.



BENITO P. BOTTERI
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ABSTRACT

This report deals with the effects of liquid fuel motion on the flammability of hydrocarbon turbine fuels in aircraft fuel tanks. Three military turbine fuels, JP-4, JP-5, and JP-8, were used in the testing. The fuels were placed in an explosionproof cylindrical test vessel (80-gallon capacity) and subjected to slosh and vibration. An electric arc was formed within the ullage which ignited any flammable fuel-air mixture present. The pressure rise from combustion was measured and correlated with initial conditions. The major effect of fuel slosh and vibration was to lower or abolish the lean flammable temperature limit of the fuel. The rich flammable temperature limit was unchanged. An analysis was performed on these results and an explanation proposed based upon the hypothesis that all the fuel vapor in the ullage burns for combustion below the flash point.

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SECTION I

INTRODUCTION

The flammability range of jet fuels under confined space conditions is usually characterized by two fuel-air concentrations: the "lean limit" at which there is insufficient fuel to enable flame propagation and the "rich limit" where there is an excess of fuel to support combustion. These limits apply to fuel in the vapor form homogeneously mixed with air. Since the vapor pressure and, therefore, the amount of fuel vapor, depends upon the temperature, these flammability limits may also be expressed in terms of temperature for any constant total pressure condition. These limits also depend upon the particular apparatus, procedure, and criteria used in testing. Standard flammability-limit test procedures and equipment have been established by the Bureau of Mines and the American Society for Testing Material (ASTM). Unfortunately, because of the dynamic environment conditions which exist in aircraft fuel tanks, the standardized test methods do not provide a valid assessment of the relative flammability range of jet fuels and consequently their vulnerability to explosions induced by various ignition sources such as electrical sparks and gunfire.

This report presents the results of a program directed toward a quantitative assessment of the influence of sloshing and vibration, such as is experienced in-flight, on the flammability limits of JP-4, JP-5, and JF-8 fuels.

Approximately 700 data tests were conducted in the program. Major emphasis was placed upon the effect of fuel slosh on the flammable temperature limits as influenced by temperature and pressure. Also investigated were the effects of vibration.

SECTION II

GENERAL PROBLEM

Flammability limits are ratios of fuel molecules to oxidizer molecules and are most often given in the literature as either mass or volume ratios. In the case of hydrocarbon turbine fuels, the mass flammability limits are approximately the same for every fuel. However, because of the differences in the molecular weights of these fuels, the volume flammability limits vary inversely to the molecular weight.

Hydrocarbon turbine fuels are liquid at temperatures experienced within aircraft fuel tanks. Therefore, in any fuel plus air environment, such as in aircraft fuel tanks, the amount of gaseous fuel mixed with the air depends upon the vapor pressure of the fuel. The vapor pressure is a function of temperature and thus the gaseous fuel concentration is a function of temperature. The fuel vapor concentration can then be expressed as a temperature. The flammability limits which, in reality, are fuel-air molecule ratios are often spoken of as temperature limits for a given air pressure or total system pressure. Because of large differences in molecular mass and volatility of fuels, the flammability temperature limits vary greatly between fuels.

Another useful characteristic of turbine fuels is the flash point. This point is the lowest temperature at which vapors above a liquid fuel surface will "flash" when exposed to an ignition source. The flash point is, therefore, very close to the lean temperature flammability limit.

Flash points and flammability limits usually depend on the test apparatus. For this reason standard test apparatus and procedures have been adopted for measuring these fuel characteristics (Reference 1). Variation in apparatus geometry and material of construction, type and energy of ignition source, and criteria from that used in the standard measurements can give flammability limits and flash points significantly different from the standard values.

Even when these standard (static) flammabilities are applied to static aircraft fuel tanks, difficulties are encountered. The addition of dynamic

conditions makes application of static flammabilities to aircraft fuel tanks extremely vulnerable to error. Dynamic conditions found in aircraft fuel tanks are motion of the tank, fuel, and air; changes in the volume of the fuel and air; and changes in temperature.

The fuel-to-air ratio is shifted when dynamic conditions are present as during an aircraft mission. Fuel sloshing and vibrating causes droplets, mists, and foams to be formed which, when combined with proper amounts of fuel vapor and air, will support combustion. Pressure changes (reductions) can result in the formation of mists which are relatively stable and may change the flammability characteristics of the ullage gases.

The application of static flammability limits to the dynamic environments found in aircraft fuel systems can lead to gross errors in the assessment of fuel tank fire and explosion hazards. In investigations performed for the FAA, Nestor (Reference 2) has shown that the lean flammability limit temperatures for turbine fuels undergoing vibratory motion can be lowered by as much as 60°F. It is, therefore, imperative that any attempt to describe fire and explosion hazards in aircraft fuel tanks incorporate the effects of the dynamic environment.

The flammability of a fuel vapor and air mixture can, in most cases, be specified by a fuel-air density profile. When fuel droplets are added to this mixture, not only must the density distribution of the droplets be specified, but the size distribution must also be given (Reference 3). Thus the flammability limits for fuel vapor in air can be specified by fuel-to-air mass ratios, but for droplets this flammable fuel-to-air mass ratio depends upon the droplet size. The amount of fuel vapor present in an aircraft fuel tank under equilibrium conditions depends upon the vapor pressure of the fuel which, in turn, depends upon the temperature. Therefore, for a given air pressure, the flammability limits for fuel vapor are often specified by the temperatures corresponding to the flammable fuel-to-air mass ratios. Determining droplet size and density is extremely difficult and, consequently, quantitative combustion data on multi-droplet systems is very scarce.

One would suspect that the addition of fuel droplets to fuel vapor would increase the effective fuel-to-air ratio of the system. Therefore, by adding droplets to a vapor-air mixture, one should be able to shift the effective fuel-to-air mass ratio into a region of different flammability. Attempts have been made to change a flammable vapor-air mixture into a nonflammable vapor-droplet-air mixture by shifting the effective fuel-to-air ratio into the rich region (Reference 4). The droplets were introduced by spraying fuel through the ullage. Partial success was achieved in that the rich flammable limit was lowered approximately 35°F. It was found that the spray nozzle that produced the smallest droplets was the most effective. When the densities of droplets which had to be used to achieve even this partial success in shifting the rich temperature flammability limit are considered, the droplet densities expected from slosh-vibration in aircraft will have negligible effect on the rich limit.

The effects of droplets on the lean flammability temperature limit are much more noticeable. Indeed, when sufficient droplet size densities are introduced, any given fuel tank ullage can be made flammable. Fuel droplets can combust in an atmosphere without any premixed fuel vapor. Therefore, the concept of a flammability temperature limit has meaning only in the vapor-droplet region in which rapid combustion cannot occur without the presence of some vapor. For an aircraft fuel tank subjected to dynamic conditions, one would suspect that droplet densities would depend upon position within the tank. Droplet densities great enough to support rapid combustion independent of vapor would occupy only a small volume of the tank. The volume for which combustion is vapor-droplet dependent should be much larger. Except in very severe dynamic conditions, there would probably be regions of an aircraft fuel tank in which the droplet density would be almost nil and, therefore, depend entirely upon vapor combustion.

SECTION III

APPROACH

1. VARIABLES

This investigation was approached by first determining the independent variables involved, deciding which ones would be controlled, and selecting those to be controlled and varied. The independent variables considered significant were temperature, pressure, pressure change rate, fuel type, fuel volume, tank material and geometry, ignition source characteristics, position of ignition source, dynamic mechanical conditions, and air humidity. All the independent variables mentioned so far were controlled. All others were considered irrelevant and hopefully negated in effect by random acquisition of data with respect to the particular independent variable being varied at the time.

The major emphasis of the investigation was placed on the effect of fuel type, temperature, pressure, and dynamic mechanical conditions on the observed reactions. The dynamic mechanical conditions investigated were fuel slosh and vibration. As baseline data, tests were also conducted under static mechanical conditions.

After selection of the independent variables came the selection of the dependent variables to be measured. In an aircraft fuel tank, the main concern with fire and explosion is the structural damage which it may cause. Keeping this in mind, pressure is the logical dependent variable to be measured. Only in a sustained fire would temperature be of great importance. These experiments, however, were not designed to investigate sustained fires but only the limit conditions under which combustion was initiated.

Pressure has another quality which makes it suitable as the primary indicator of the combustion which has taken place. Pressure is an integrated measurement of the total combustion and does not depend upon the location of the pressure gauge.

2. TEST APPARATUS

The test vessel (Figure 1) used for these experiments was approximately 80 gallons in capacity and stainless steel in construction. It was cylindrical in shape with a 20-inch outer diameter and about 5 feet in length. Its walls were 3/8 inch thick, and it had been tested to safely withstand 300 PSIA at room temperature. An 8-inch viewing port was located at each end and a pressure-relief burst disk was located on the top of the circular wall. This disk, however, was converted into a view port for these experiments. One end of the tank was a rapid opening door.

This test chamber was mounted on a slosh-vibration table located at Wright-Patterson AFB, Ohio. Vibration is defined as displacement perpendicular to the surface of the table. Slosh is defined as a rocking motion of the table surface about an axis located in the table surface. The test chamber's cylindrical axis was parallel to the table surface, perpendicular to the sloshing axis, and centered above the sloshing axis. The table could vibrate at frequencies between 400 and 3200 CPM and double amplitudes up to 0.050 inch. It could slosh at frequencies between 10 and 20 CPM and double amplitudes between 16° and 30°. Slosh amplitude was not readily adjustable and was set at 30° for all the tests. Slosh and vibration frequencies and amplitudes could be varied independently.

Fuel was heated by means of a steam heat exchanger and cooled by storage in a specially adapted commercial food freezer (Figure 2). Air entering the test chamber was passed first through a chemical air dryer (Figure 3). Vacuum was applied by oil vacuum pumps.

The chamber was instrumented by two copper-constantan thermocouples: one mounted in the ullage and one submerged in the fuel. The thermocouple outputs were recorded by a Brown "Elektronik" recorder. Pressure was measured by two strain gauge transducers mounted in the ullage (Consolidated Electrodynamics Corporation Type 4-326-0003, 0-75 PSIA; and CEC Type 4-311, 0-200 PSIA). An uncalibrated photodiode was also mounted in the chamber so that it viewed the vicinity of the ignition source. The pressure transducers and

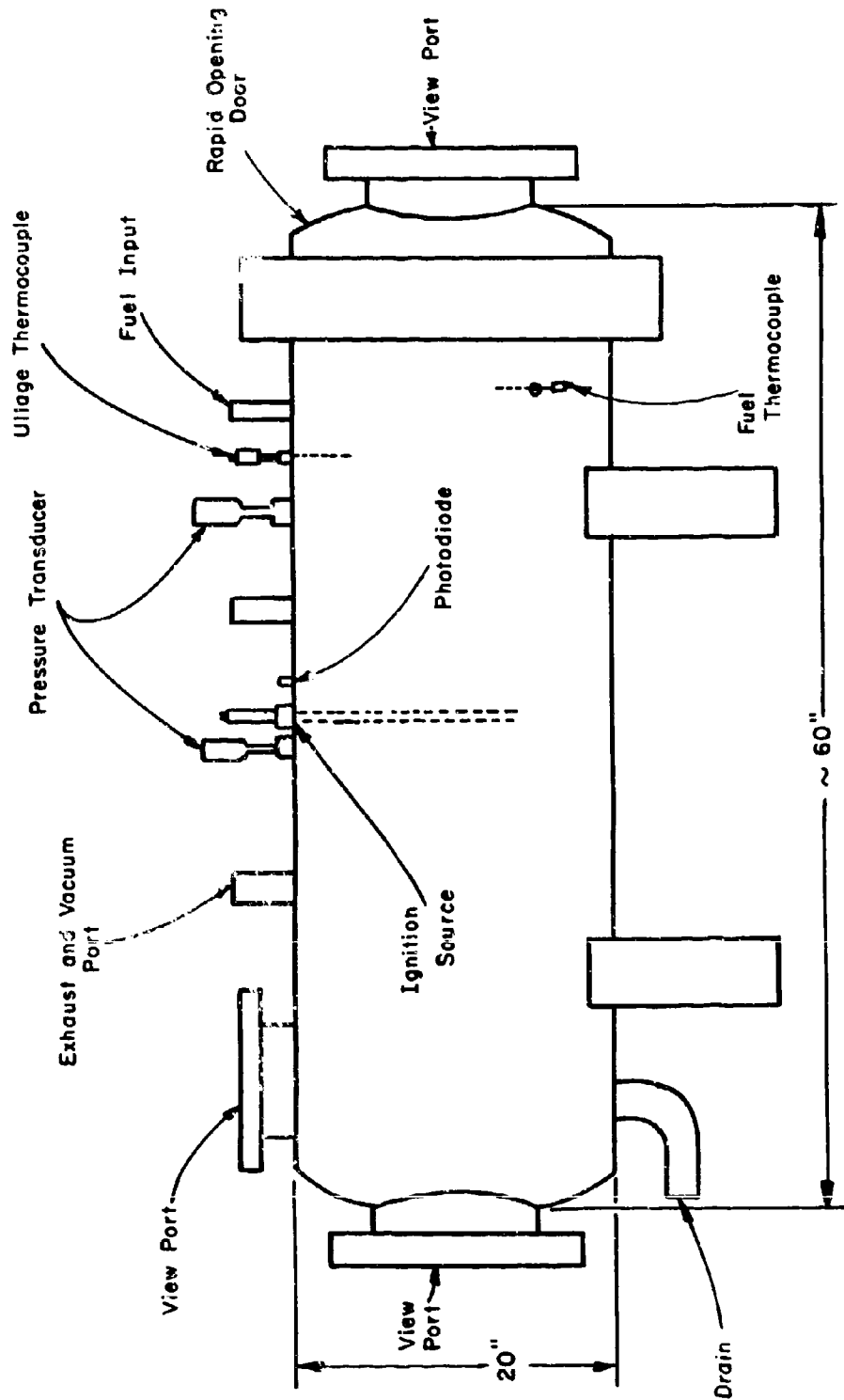


Figure 1. Instrumented Test Chamber

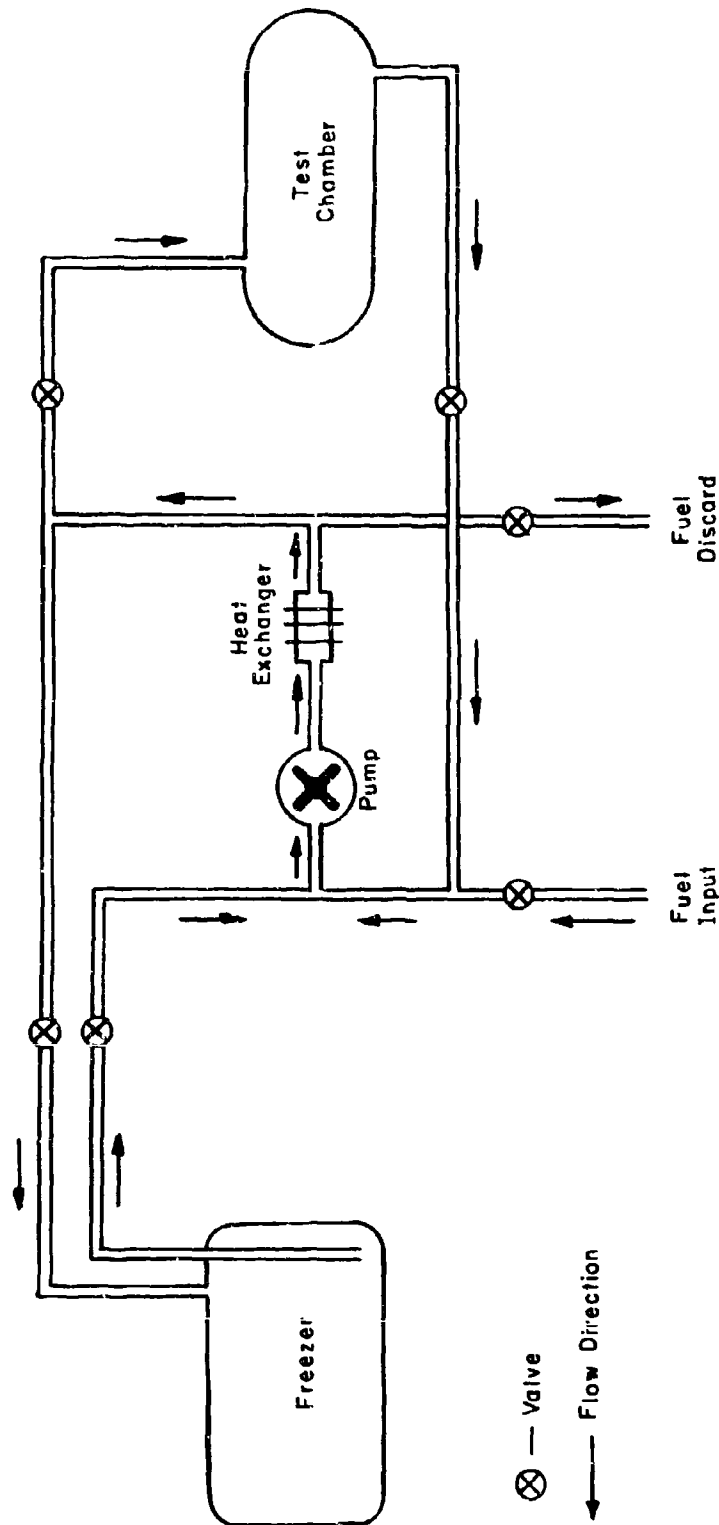


Figure 2. Fuel Temperature Control System

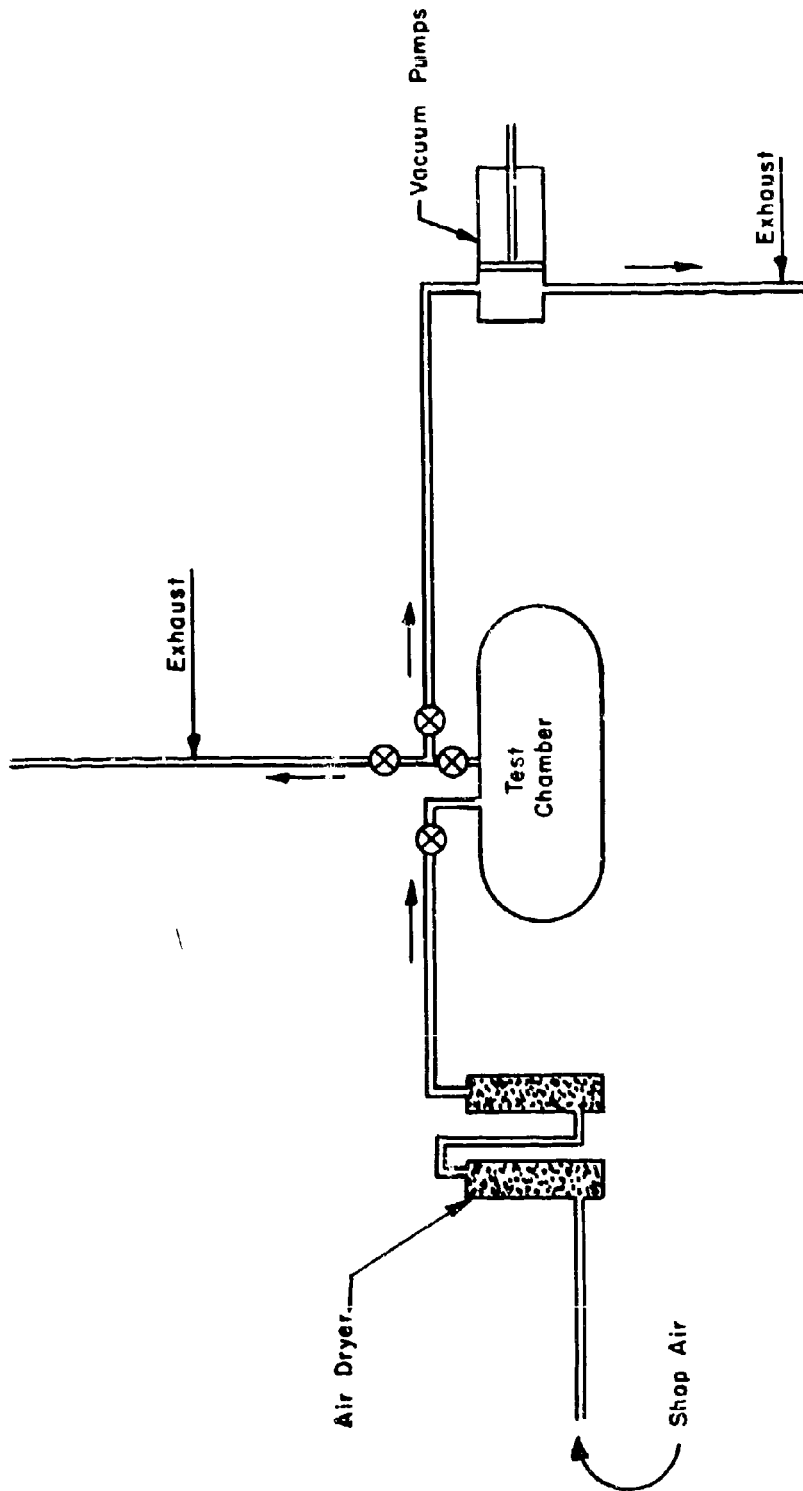


Figure 3. Ullage Pressure Control System

photodiode outputs were recorded on a light beam oscillograph (CEC Model 5-124). Also recorded on the oscillograph was the output of an uncalibrated accelerometer which sensed the sloshing motion of the table.

The ignition source (Figure 4) consisted of two 1/16-inch stainless steel rods mounted nearly parallel and vertically from the top center of the test chamber. These rods were separated by approximately 1/4 inch. A standard furnace-type fuel-oil ignition transformer rated at 12,000 volts AC and 25 milliamperes was used to apply voltage to the rods. These rods were insulated from the test chamber but had a length of 12 inches exposed to the ullage. The bottom ends of the rods were mounted closer together than the top so that an arc formed at the bottom when the high voltage was applied. The convective air currents formed by the hot arc forced the arc up the rods to a point at which the separation was too great to sustain the arc. Here the arc was broken and a new one formed at the bottom.

3. TEST FUELS

JP-4, JP-5, and JP-8 (similar to Jet A-1) fuels as specified by MIL-T-5624 and MIL-T-83133 were used in the testing. The average molecular weights, flash points, and vapor pressures of these fuels are given in Appendix I.

4. TEST PROCEDURES

Fuel was pumped from the storage bin or freezer into the test chamber. If the fuel was to be heated, heating was accomplished by circulating the fuel in the test chamber through the steam heat exchanger.

Before any test was conducted, the ullage was evacuated to approximately 1 PSIA. Evacuation was performed with the fuel in the test chamber and took about 30 seconds. Next the tank was pressurized to atmospheric pressure through the air dryer. At that point the tank was vented to the atmosphere to insure that the pressure transducers were calibrated at atmosphere. After that check, the tank pressure was adjusted to the desired value.

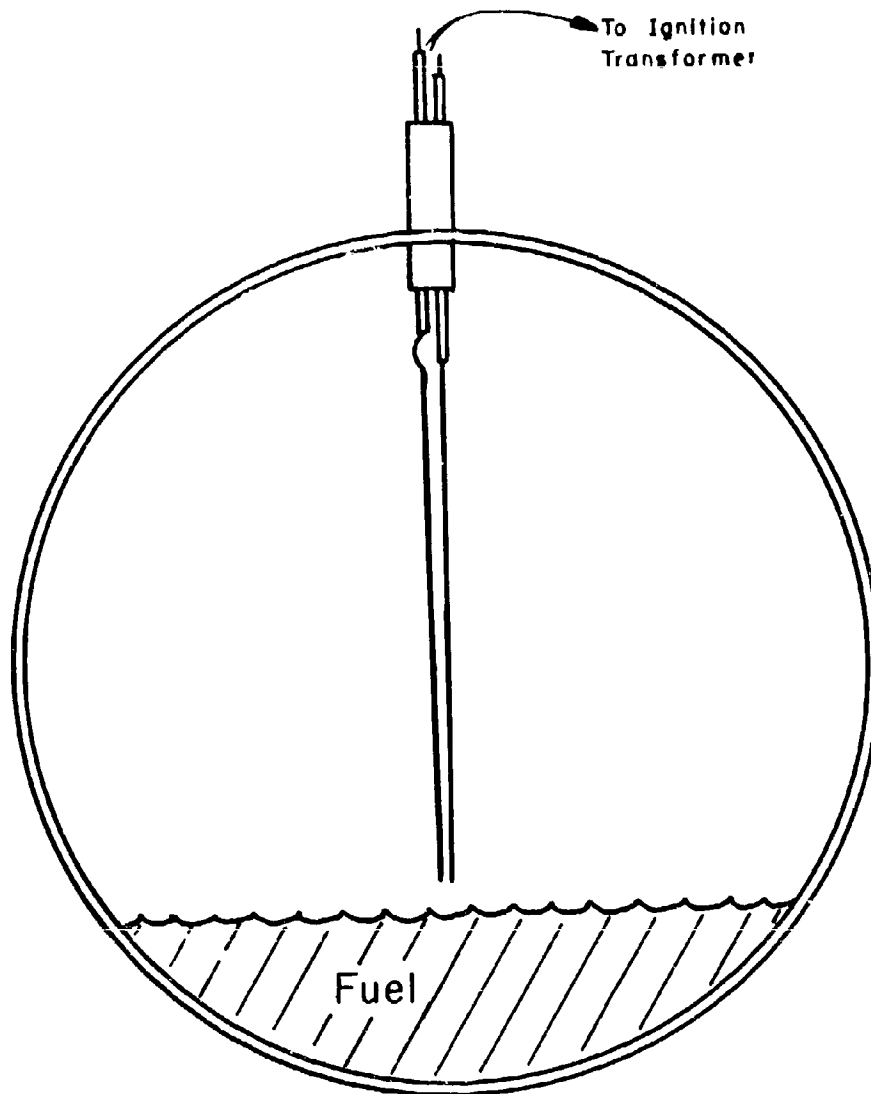


Figure 4. Ignition Source

The tank was sealed after adjusting the pressure. For 5 minutes, the test chamber was sloshed to insure that as near homogeneous and equilibrium vapor conditions existed as possible. If a static test was desired, the sloshing was stopped and ignition attempted within 1 minute. If a sloshing test was to be performed, then sloshing was continued at the desired conditions and ignition attempted. For any given test, the ignition source was activated many times in succession if ignition did not occur immediately.

After ignition or attempted ignition, the ullage was evacuated and the test procedure repeated for readying the test chamber for the next test.

Several tests were run on each fuel sample placed in the test chamber. The amount of fuel placed in the test chamber was about 10 gallons, and from 2 to 8 tests were conducted on each amount of fuel placed in the chamber depending upon the type of fuel being tested.

SECTION IV

RESULTS

1. STATIC TESTS

Static fuel vapor ignitions were performed to serve as baseline data for the evaluation of the effects of dynamic conditions. Typical results are shown in Figures 5 and 6. The lean flammable temperature limits occurred approximately at the flash points of the fuels. Figures 7 and 8 give peak reaction pressure rises for lean static ignitions at various initial ullage pressures. These overpressures correlate very well with the function $\Delta P = \alpha P_v$, where ΔP is the peak reaction pressure rise, P_v is the fuel equilibrium vapor pressure, and α is a constant.

2. SLOSH TESTS

a. Rich Flammable Temperature Limit

No effect of fuel slosh on the rich flammable temperature limit was observed. Figure 9 shows static and slosh ignition with JP-4 in the rich region.

b. Lean Flammable Temperature Limit

Fuel slosh lowered the lean flammable temperature limit. Typical slosh pressure pulses are shown in Figures 10 and 11. The magnitude of this extended flammable region varied directly with the degree of fuel agitation. Figure 12 shows the effect of slosh frequency on peak overpressures. The amount of fuel agitation increases with increasing frequency. For worst case slosh conditions at one atmosphere initial pressure, the lean limit was lowered approximately 60°F. In other words, the reaction pressure decreased with decreasing temperature for 60°F below the flash point; however, pressure rises of 2-5 PSI were recorded at even the lowest temperatures tested—as much as 95°F below the flash point. For a given slosh condition, the peak reaction pressure rises in the extended region were independent of the initial ullage pressure. In the worst case slosh conditions, the peak overpressures, as in the lean static ignition case, correlate well with the function $\Delta P = \alpha P_v$. Figures 13 and 14 show the peak overpressures for JP-8 worst case sloshing at two initial pressures. The worst

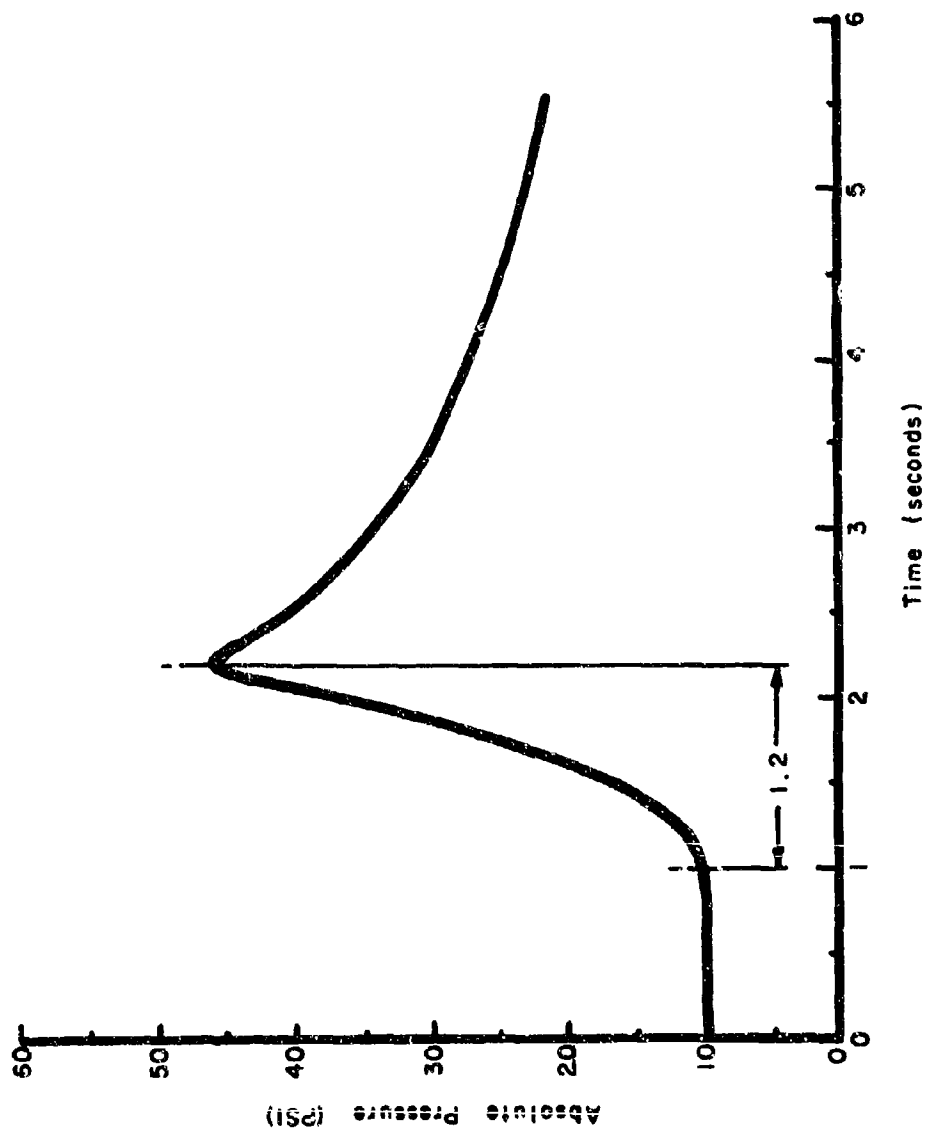


Figure 5. Typical Reaction Pressure Pulse from Static Tests (JP-8, Fuel Temperature 106°F, Initial Ullage Pressure 10 PSIA)

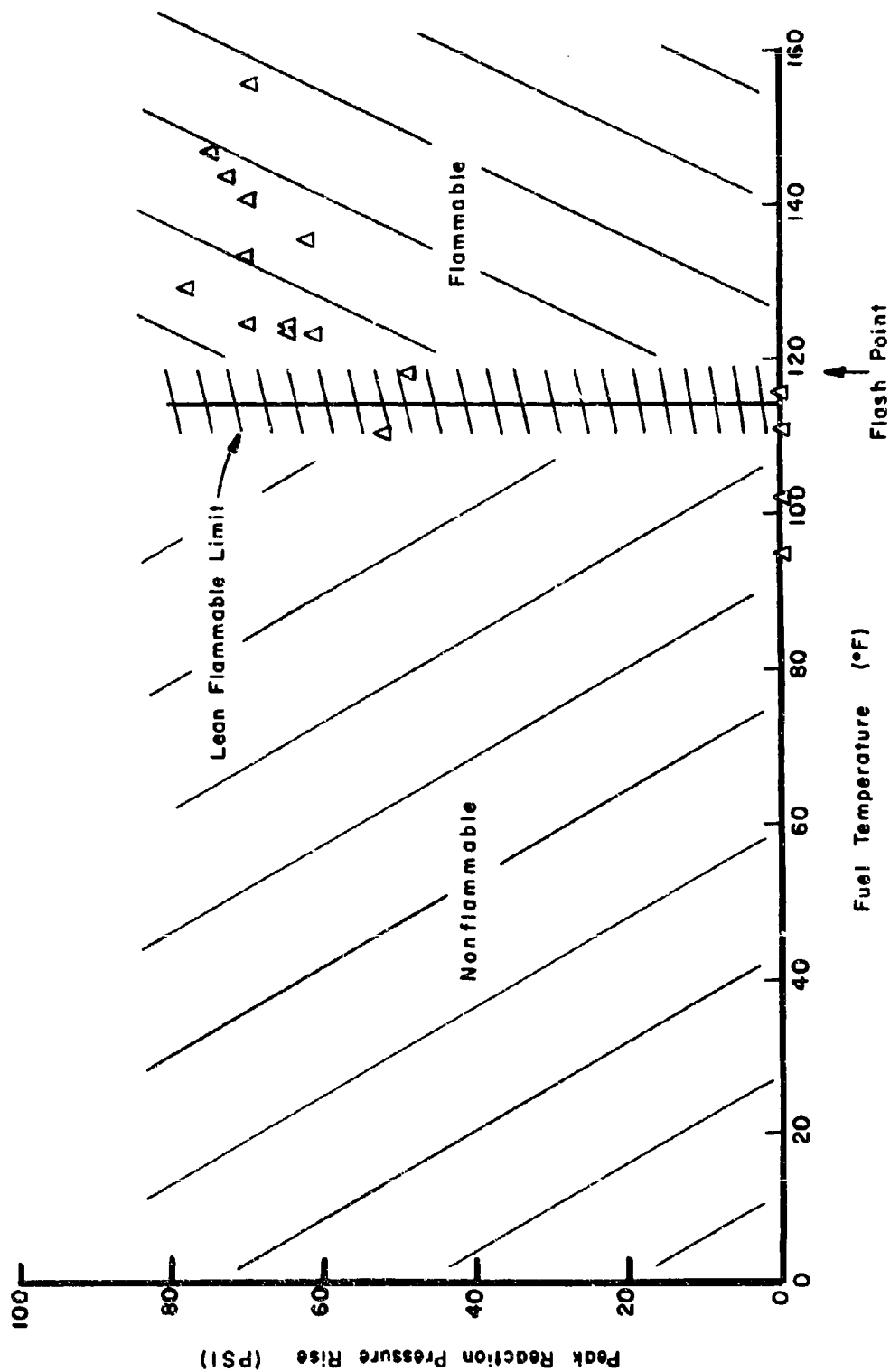


Figure 6. Lean Static Flammability of JP-8 at Atmospheric Pressure

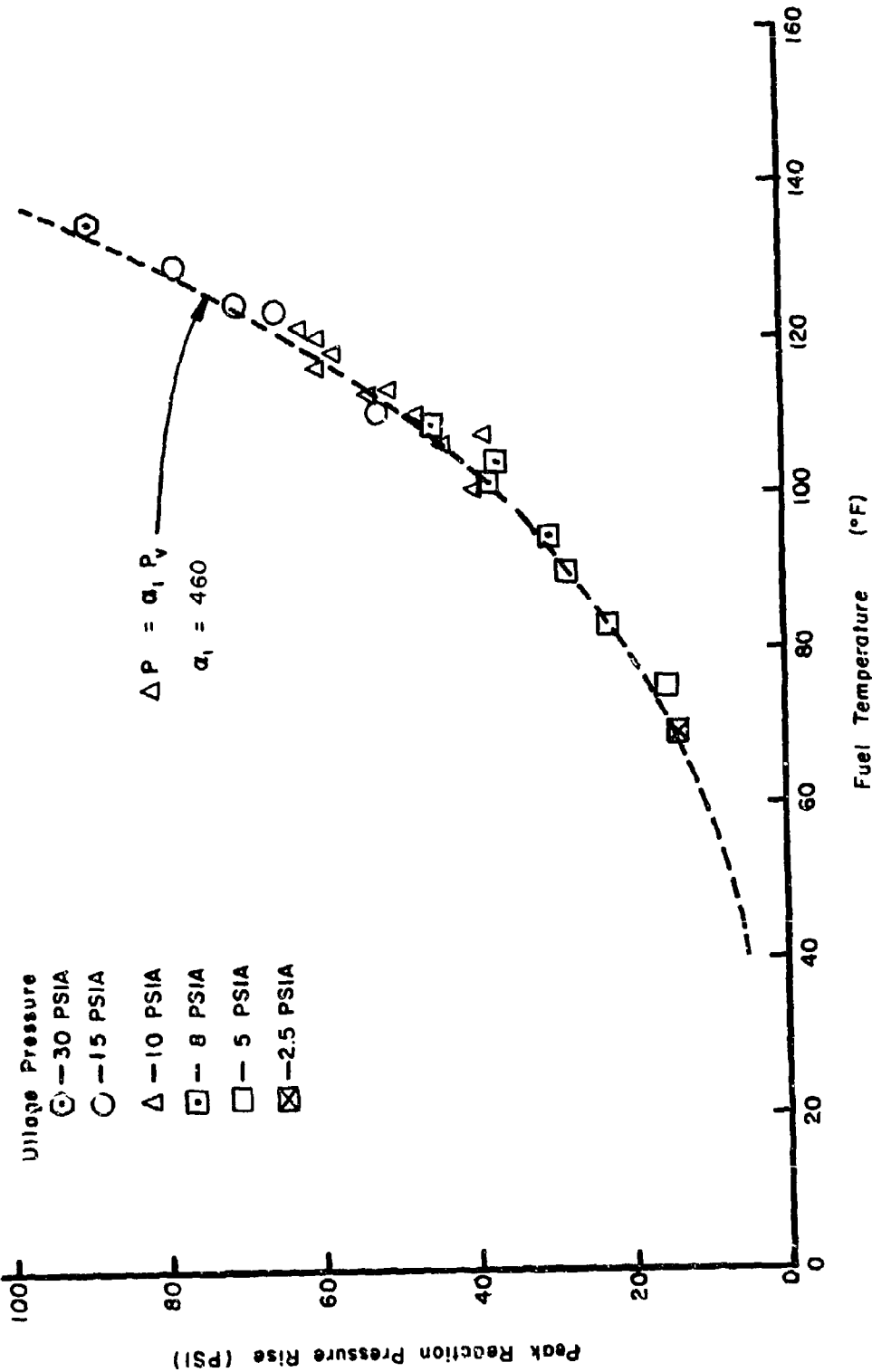


Figure 7. Lean Static Reactions for JP-8 at Various Initial Ullage Pressures
With Ignition Source in Center of Chamber

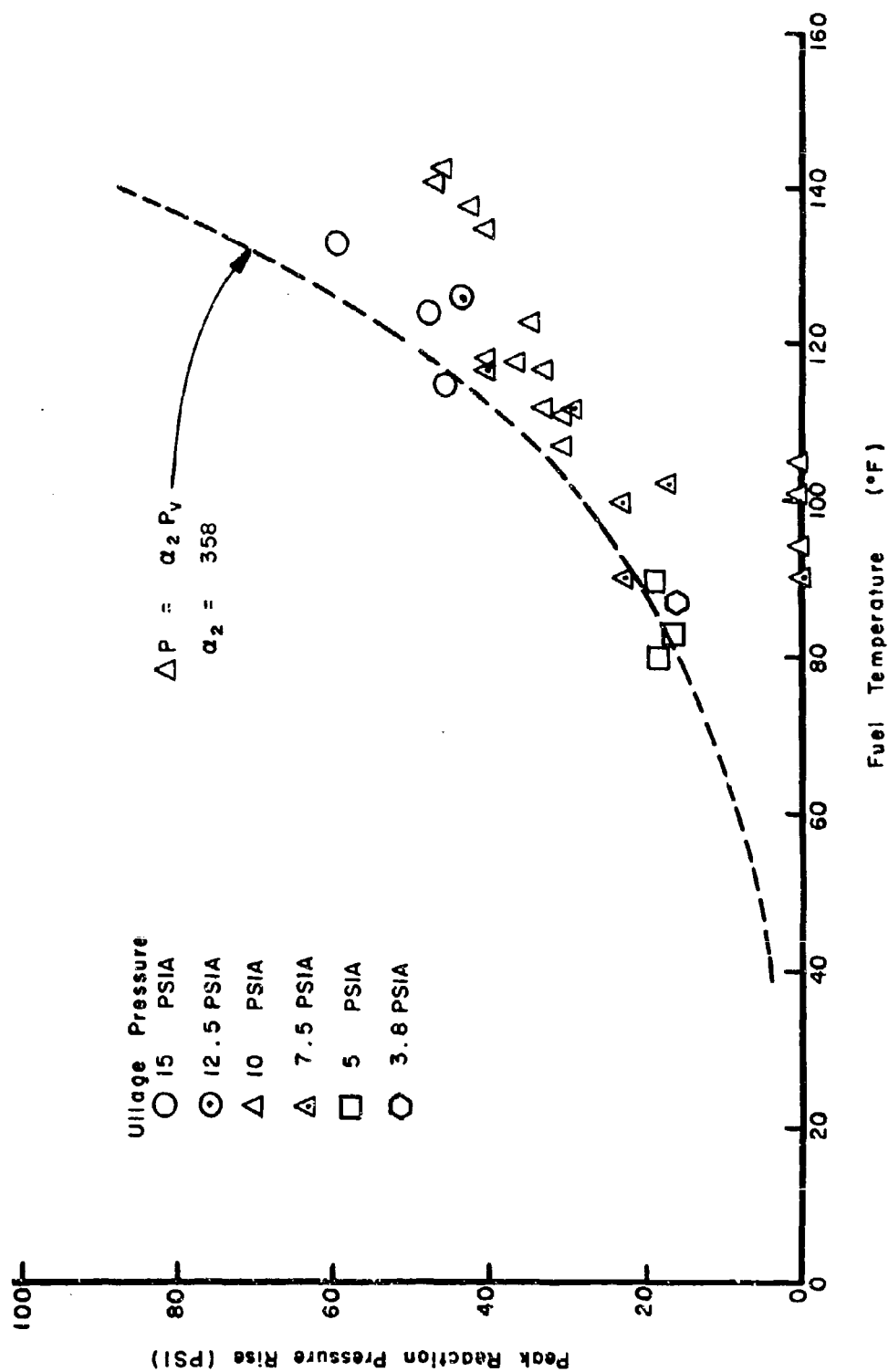


Figure 8. Lean Static Reactions for JP-8 at Various Initial Ullage Pressures
 With Ignition Source in Rear of Chamber

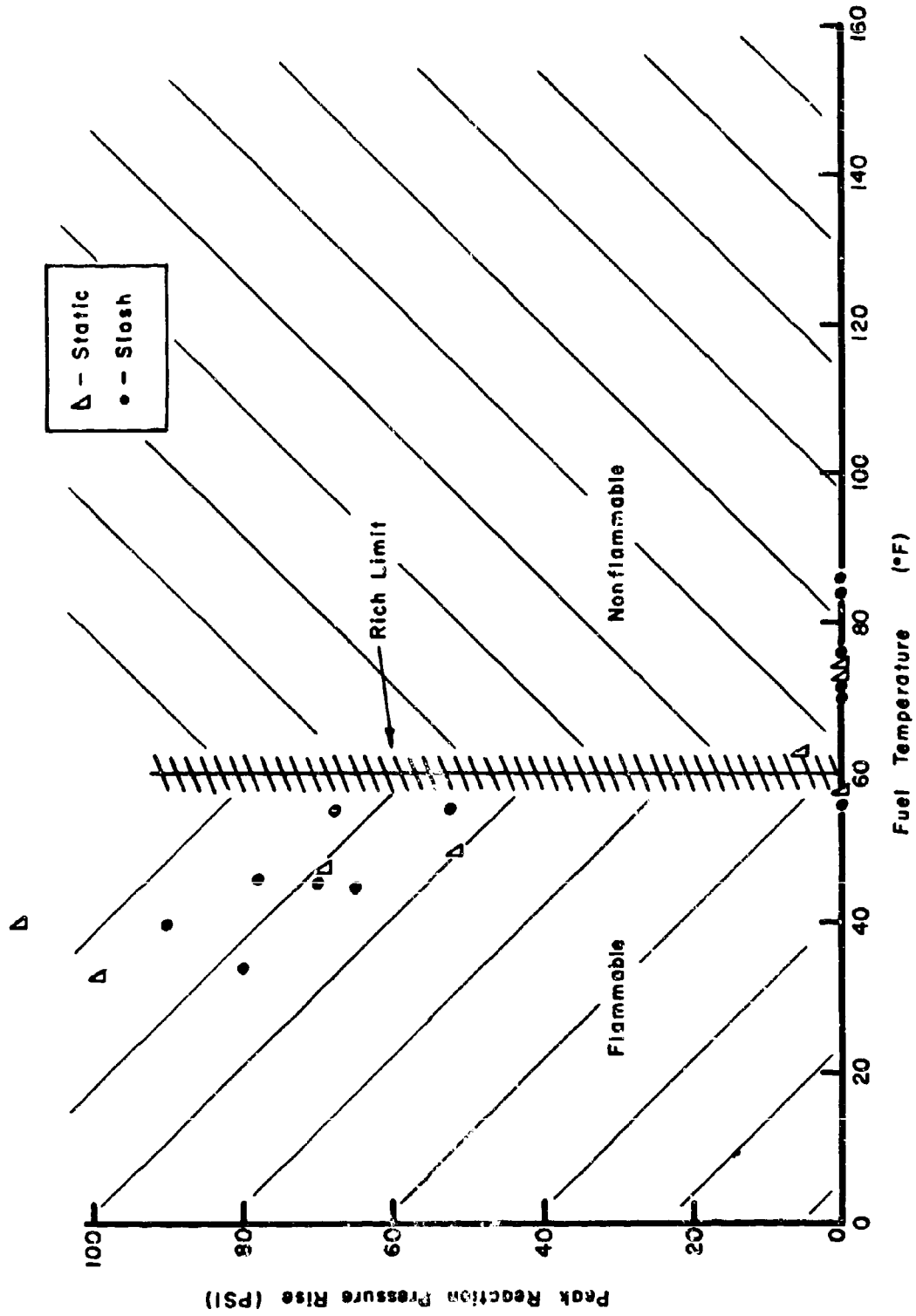


Figure 9. Rich Flammability Limit for JP-4 at One Atmosphere Initial Ullage Pressure

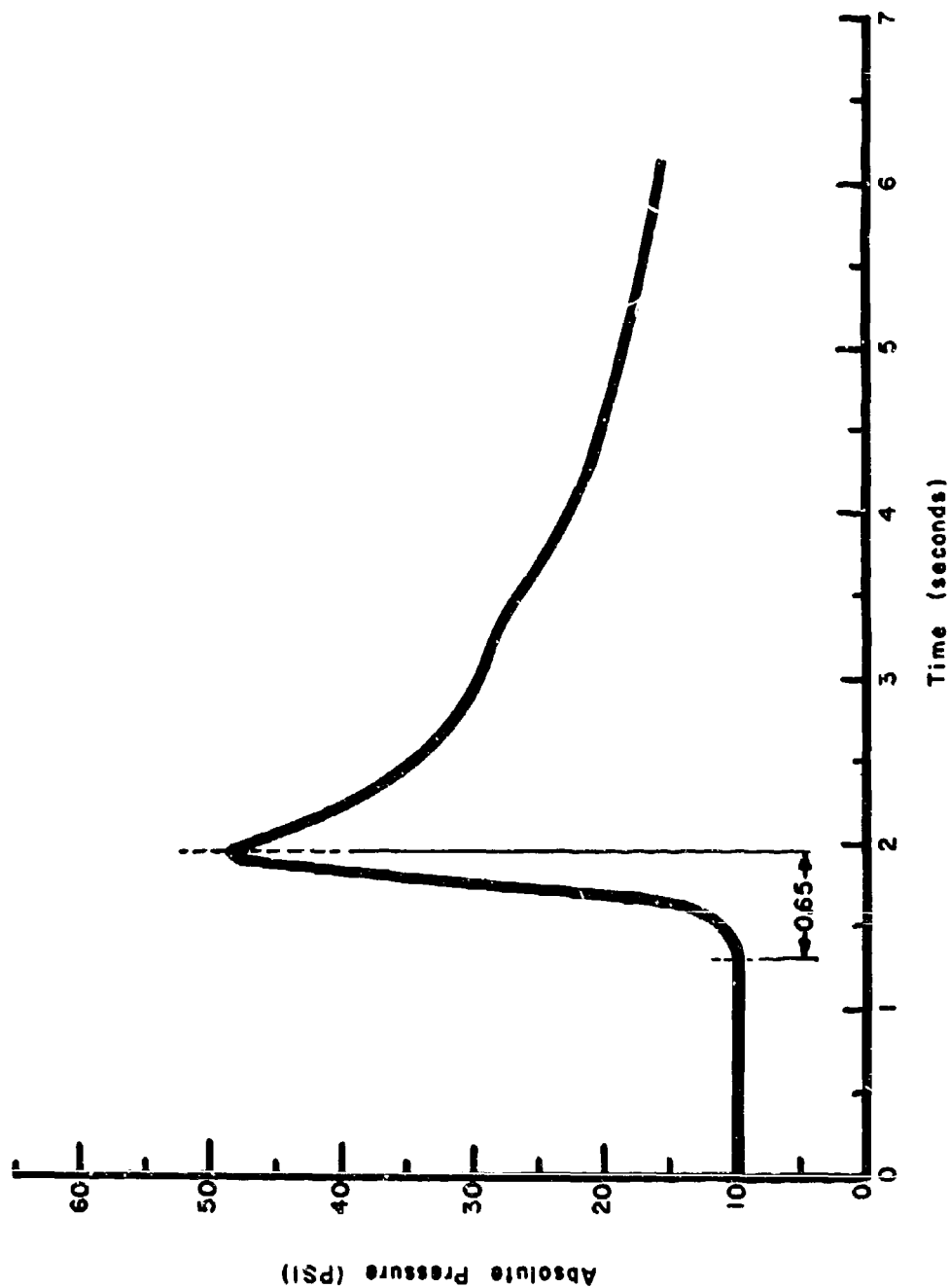


Figure 10. Typical Reaction Pressure Pulse From Slosh Tests (JP-8, Slosh Frequency at 17.5 CPM, Fuel Temperature 104°F, Initial Ullage Pressure 10 PSIA)

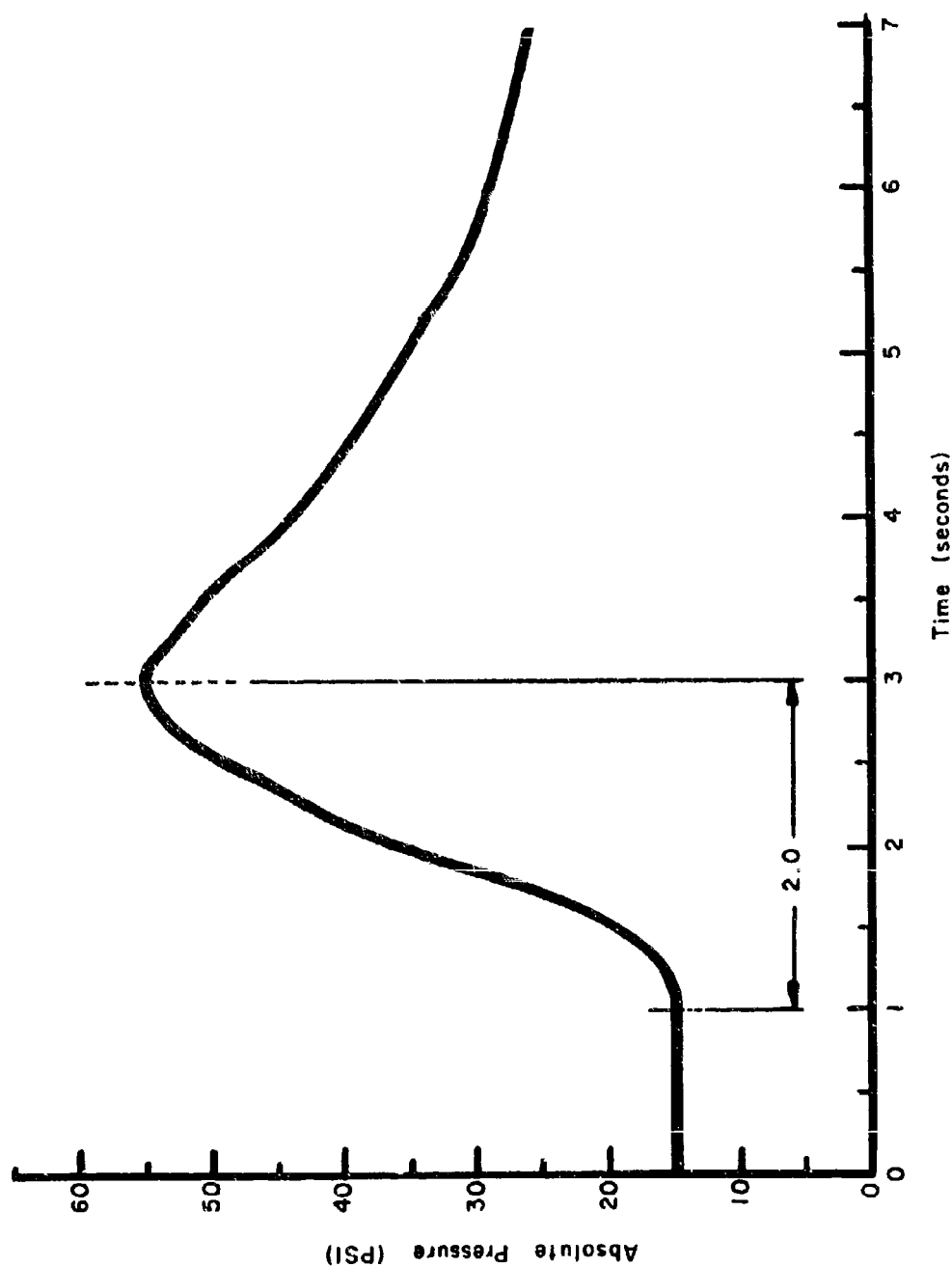


Figure 11. Typical Reaction Pressure Pulse From Slosh Tests (JP-8, Slosh Frequency at 17.5 CPM, Fuel Temperature 105°F, Initial Ullage Pressure 14.7 PSIA)

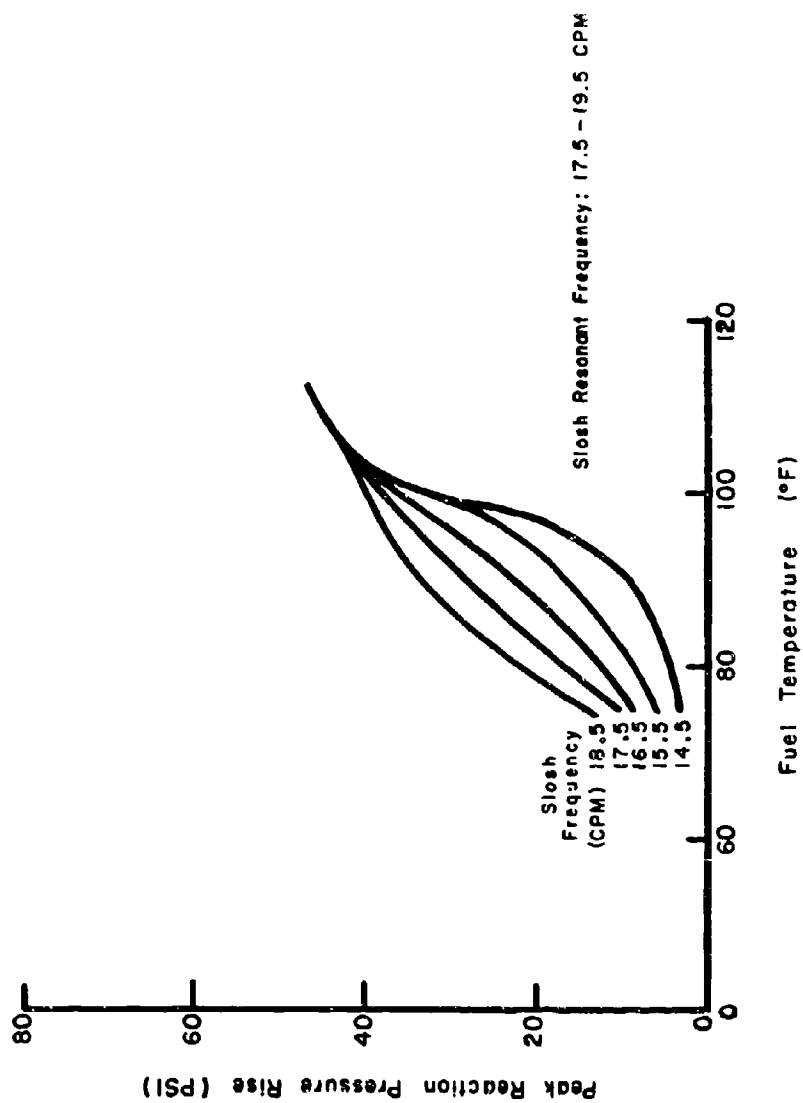


Figure 12. Effect of Slosh Frequency on Reaction

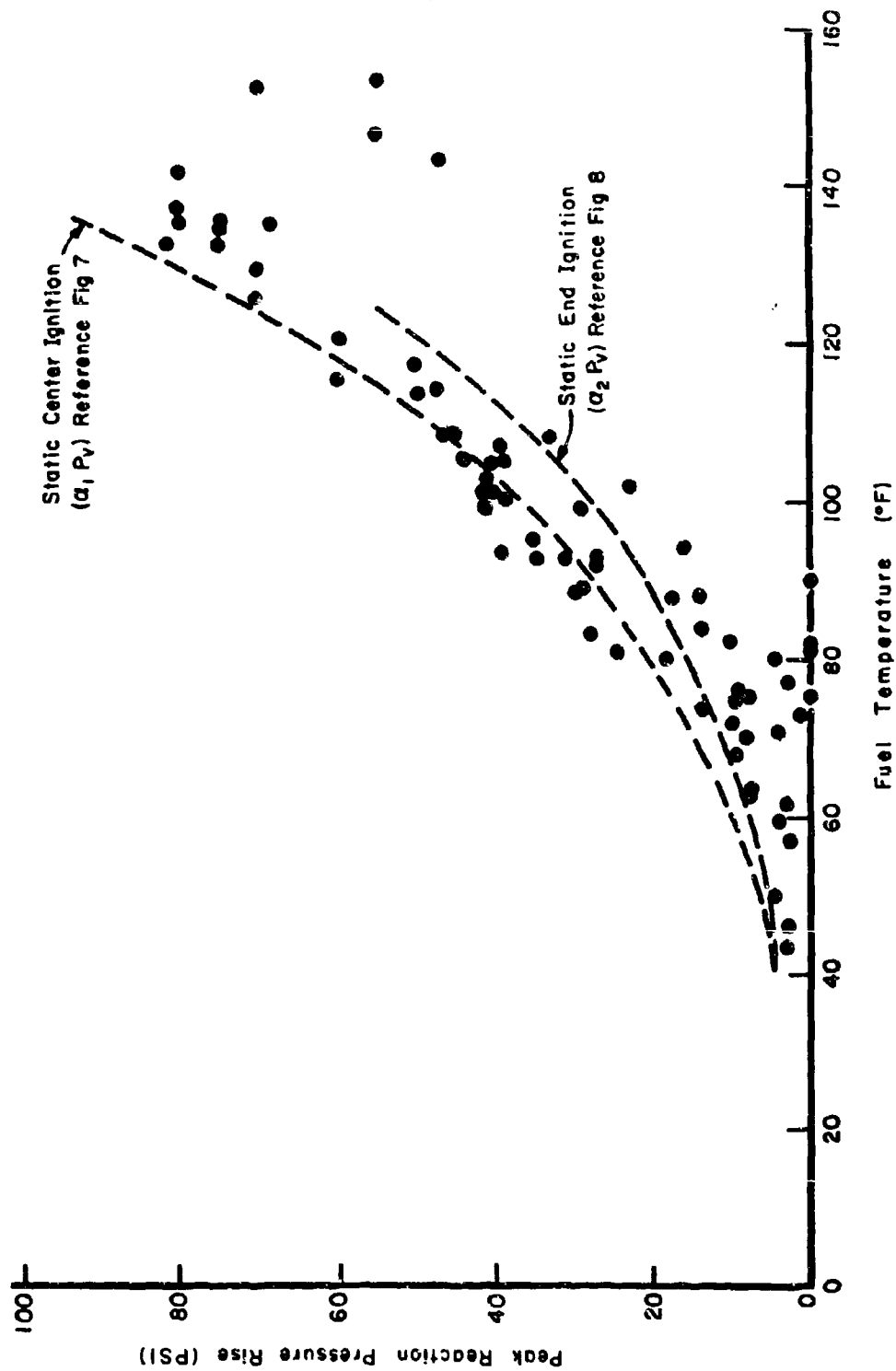


Figure 13. Extended Lean Flammability for JP-8 Fuel Sloshing at 17.5 CPM and Under One Atmosphere Initial Ullage Pressure

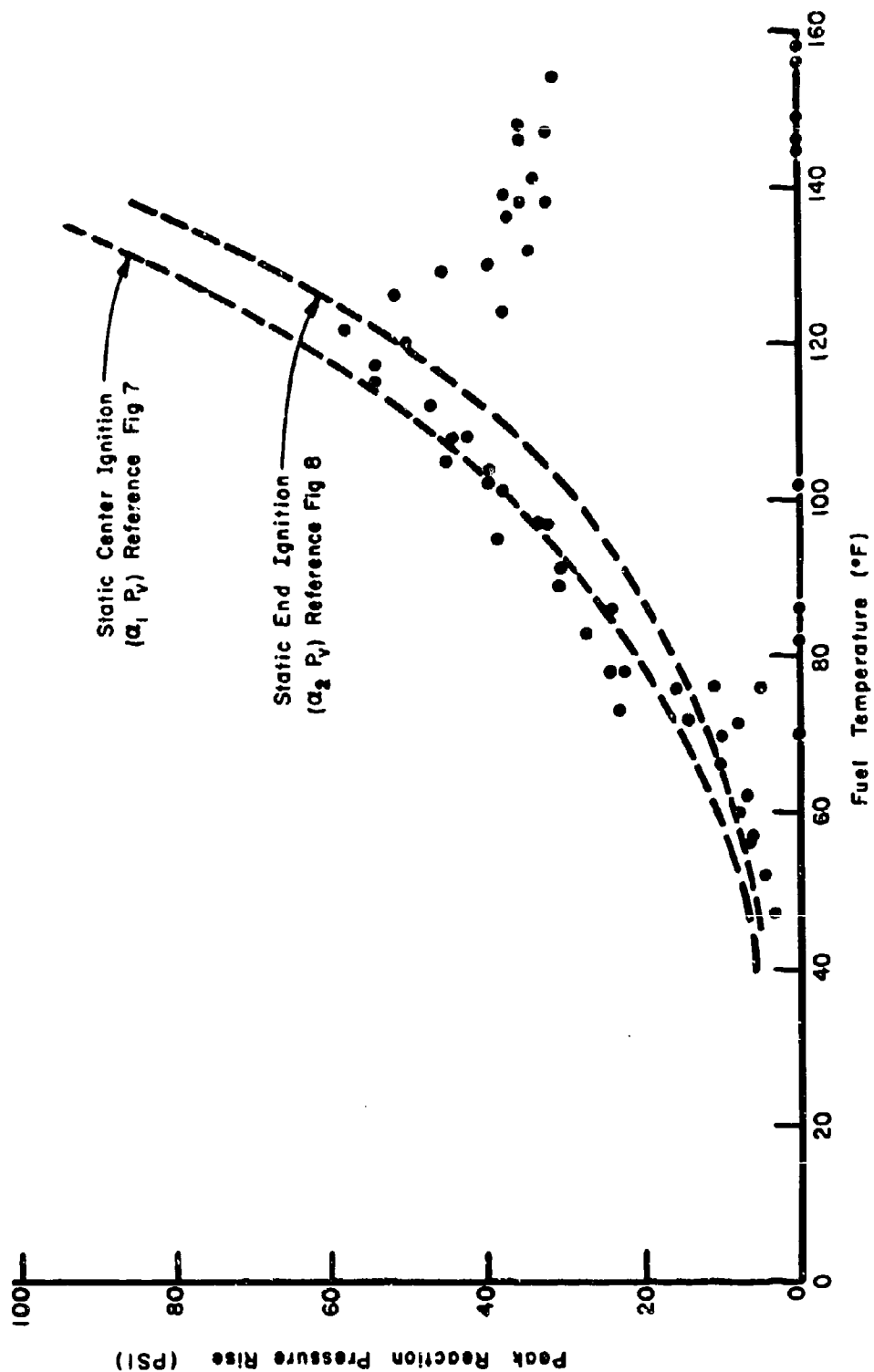


Figure 14. Extended Lean Flammability for JP-8 Fuel Sloshing at 17.5 CPM and Under 10 PSIA Initial Ullage Pressure

sloshing condition is the frequency at which the fuel moves in resonance with the driving force. These figures also compare the sloshing overpressures with the static overpressure correlations shown in Figures 7 and 8. Figure 15 shows overpressures for JP-8 at a sloshing frequency less than resonant. Figure 16 shows overpressures for JP-5.

3. VIBRATION TESTING

The effect of vibration in these tests was nil. No ignitions occurred when the fuel was vibrated. For slosh plus vibration, the results were essentially the same as for slosh alone (see Figure 17). Although vibration has the potential to agitate the fuel as great as slosh, the vibration frequencies and amplitudes which could be implemented with the equipment used in these experiments (500-3200 CPM and 0.050-inch double amplitude) were not sufficient to produce large agitation.

4. HIGH SPEED FILMS

High speed (500 frame/second) 16-mm color films were made of the combustion of representative reaction types (lean static, rich static, lean slosh, and rich slosh conditions). These films were taken at a view port located at one end of the test vessel. Such a location restricted the viewing time of sloshing reactions to one half of the slosh cycle. Since most sloshing reactions reached their maximum intensity within less time than one half a slosh cycle, the restriction on viewing time did not significantly limit the film coverage.

For lean static ignitions, a spherically propagating flame front of blue color was observed. The visible light from this flame wave appeared brighter for reactions with larger fuel concentrations. In the case of very rich static combustion, no distinct flame front or wave was seen. The combustion was orange or white in color and very bright.

When vapor concentrations which were flammable even under static conditions were ignited while sloshing, both droplet and blue vapor combustion could be observed. Only droplet combustion could be seen when normally too lean to ignite statically vapor concentrations were ignited while sloshing.

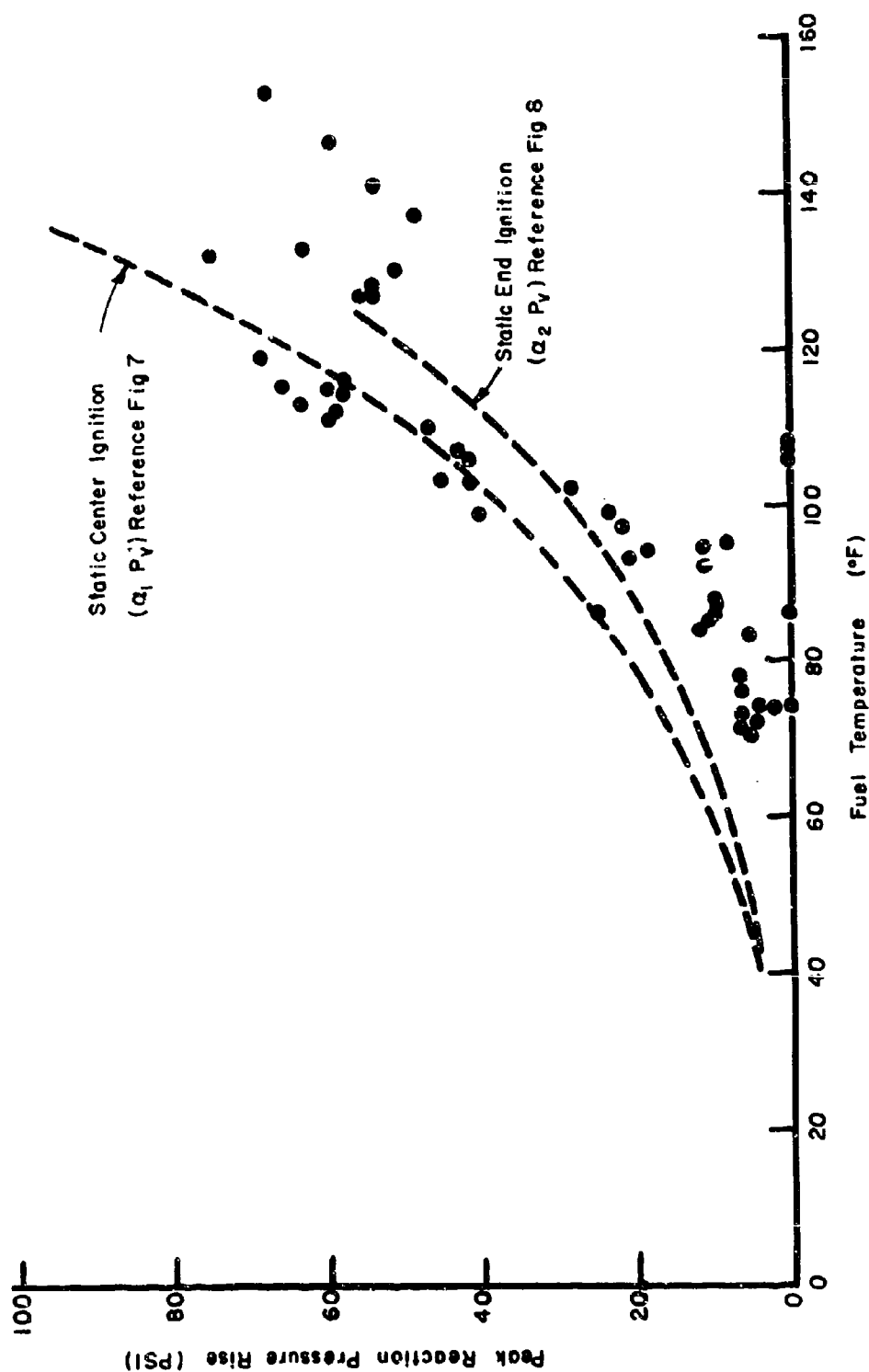
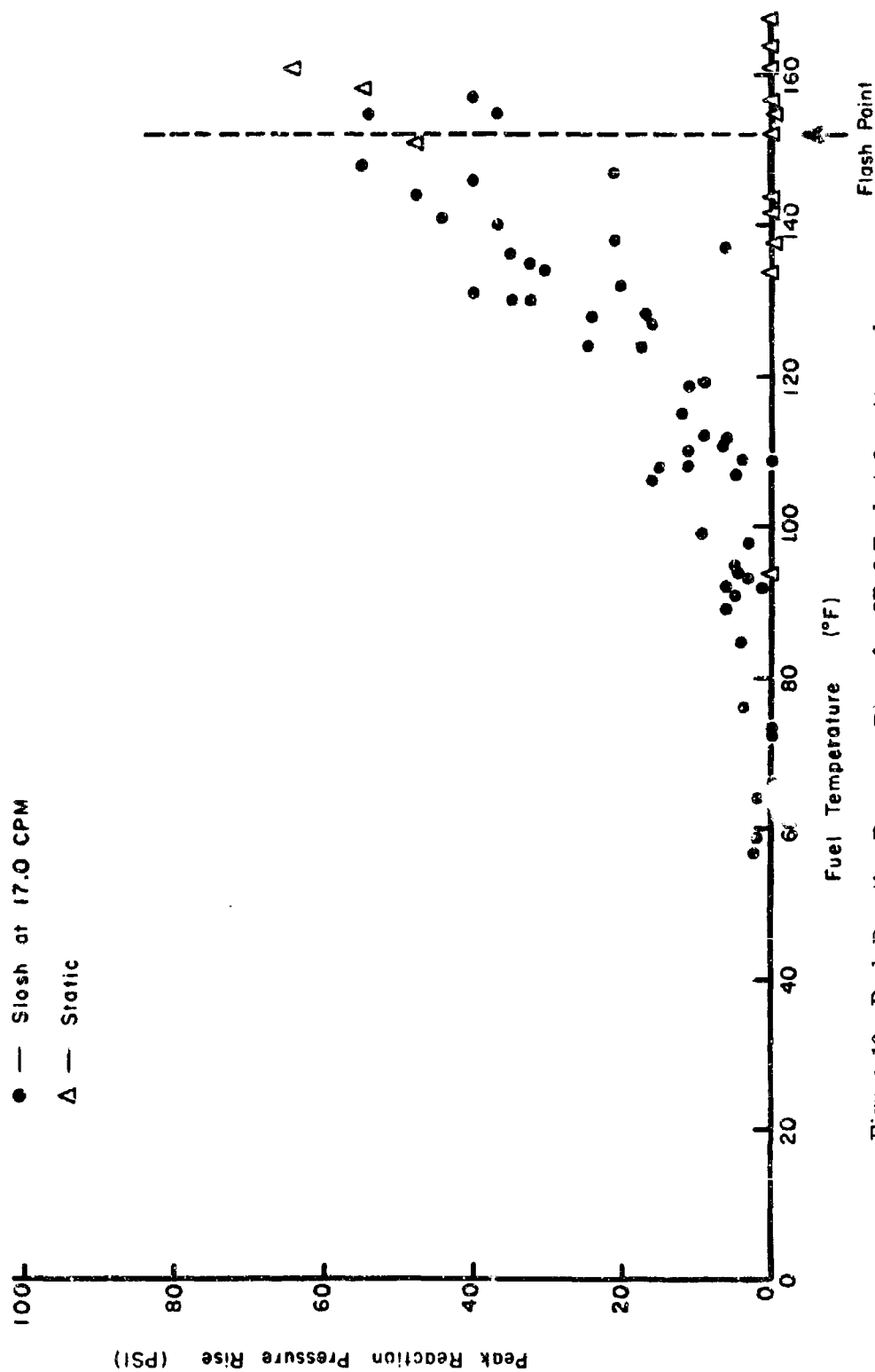


Figure 15. Extended Lean Flammability for JP-8 Fuel Sloshing at 15 CPM and Under One Atmosphere Initial Ullage Pressure



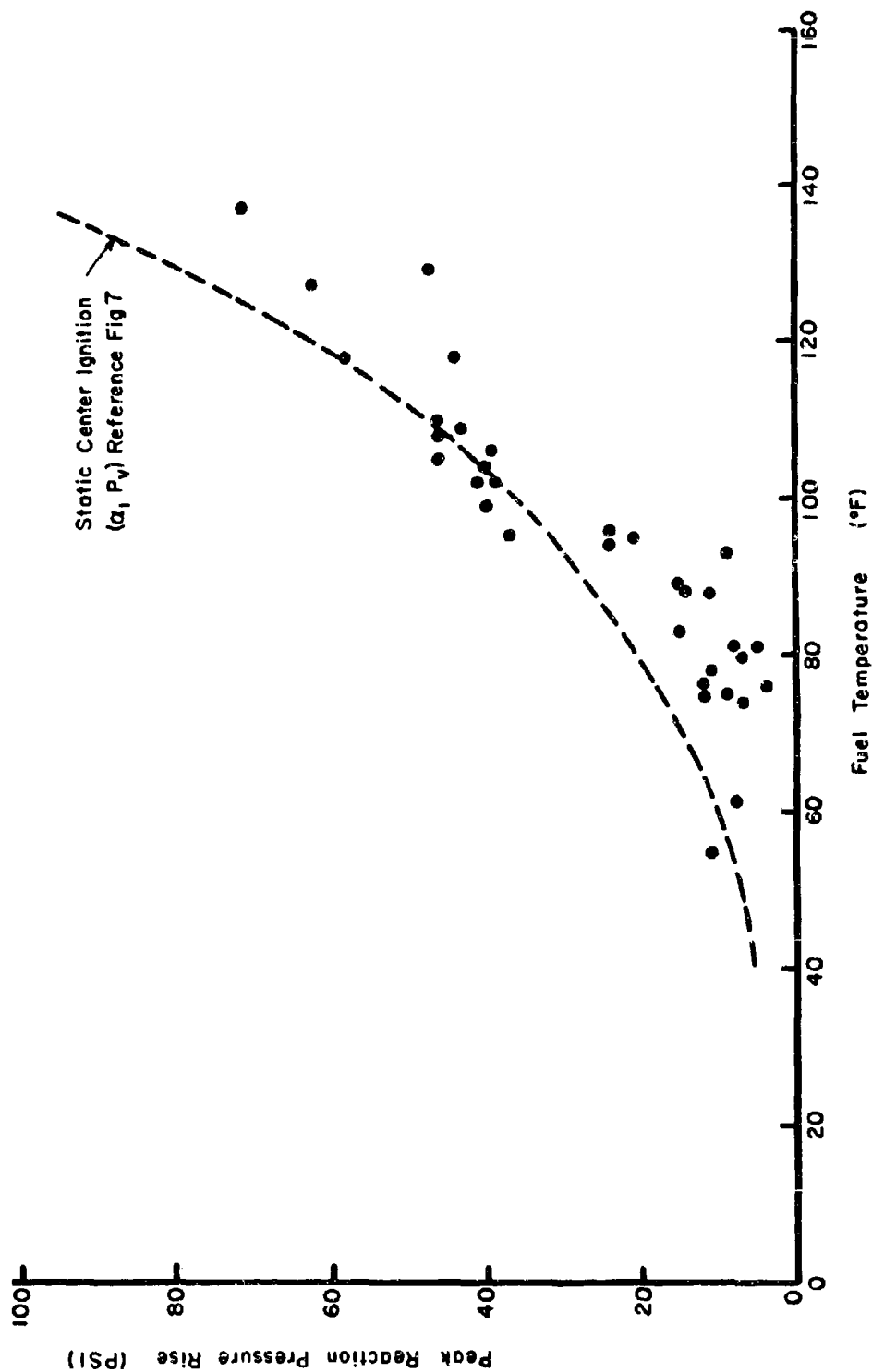


Figure 17. Extended Lean Flammability for JP-8 Fuel Sloshing at 17.5 CPM, Vibrating at 1100 CPM and 0.005-inch Double Amplitude, and Under One Atmosphere Initial Ullage Pressure

SECTION V

DISCUSSION OF RESULTS

1. GENERAL

The most immediate observation of the data is that the lean flammable vapor-air limit is no longer valid, but that there is a gradual lessening of the observed reaction as the vapor concentration falls below the flash point concentration. Also there is no observed effect of slosh conditions upon the rich limit.

Instead of a lean flammable limit under slosh conditions, there is a gradual decrease in the severity of the reactions occurring in concentrations below the static lean flammable limit. The reaction severity decreases in proportion to the amount of fuel vapor present in the ullage. This relationship provides a simple straightforward method of extending results of this experimentation to other fuels.

The severity of the lean reactions steadily decreases to a point approximately 60°F below the flash point at standard atmosphere ullage pressure. At this temperature, the peak reaction pressure is on the order of 2 to 5 PSI. Below this temperature, small pressure rises can be measured for at least 20°F. In this lower temperature range, the vapor pressure of the fuel changes only slightly in respect to its value at the flash point. It is not unlikely that reactions of 2-5 PSI could occur for almost any temperature below this 60°F extension.

2. STATIC REACTIONS

The variation of ullage pressure showed no effect upon the observed reaction pressure except to shift the rich limit. This observation applies to both the slosh and the static data. Thus a static ignition at the lean limit of JP-8 at atmospheric ullage pressure yielded the same pressure rise as a static ignition near the stoichiometric concentration for 10 PSIA ullage pressure. This result is coincidental but not highly unlikely (see Appendix II).

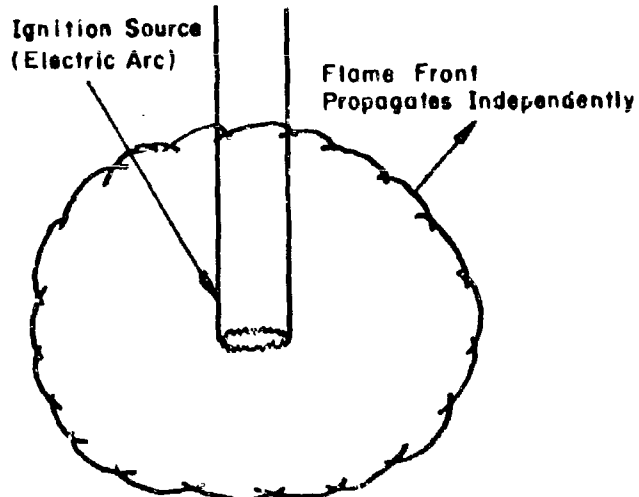
The peak reaction pressure rise appears to be entirely independent of the ullage pressure for fuel lean reactions. When the total pressure is reduced to some suitable value, the vapor present at any fuel temperature can be ignited statically at a fuel lean concentration and the resulting reaction pressure correlated directly with the fuel vapor pressure yielding the equation $\Delta P = \alpha P_v$ (see Figures 7 and 8). α is a catchall term covering the multitude of other factors (such as heat loss, tank geometry, and vapor inhomogeneity) which influence ΔP . However ambiguous α is, the value for α should be the same for homologous conditions and setups. In other words, α is the scaling factor.

3. LEAN SLOSHING REACTIONS

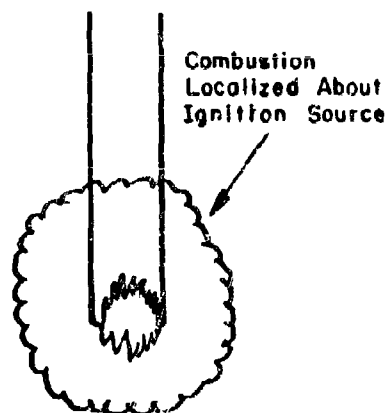
The role played by the sloshing and the fuel droplets in the combustion is still unknown. However, on the basis of this experimentation, it appears that one of its important functions is to alter the mechanism by which the flame spreads throughout the volume combusting the vapor already present.

In vapor concentrations outside the standard flammability limits, the fuel concentration is such that, in order for the vapor to combust, energy must be added to the vapors in amounts greater than normally required for ignition. This additional energy can be supplied by a localized high energy ignition source. The combustion process about such a high energy ignition source is necessarily localized about the ignition source. Without the energy from the ignition source, the energy density from the fuel vapor combustion is insufficient to ignite any new vapor. The volume of combustion about this ignition source most likely depends upon the density of fuel vapor present and the strength of the ignition source (see Figure 18). If the fuel vapor density increases toward the flammable density region, the additional energy density required for combustion decreases. Thus the volume of combustion should increase as the fuel vapor density increases.

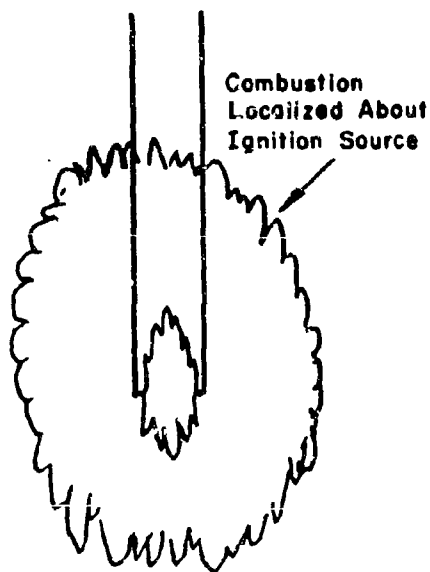
A fuel droplet offers a large surface area with a small mass, thus enabling a flame to be easily ignited about it. A burning fuel droplet might serve as a high energy ignition source for the fuel vapors. Such a fuel droplet-vapor system



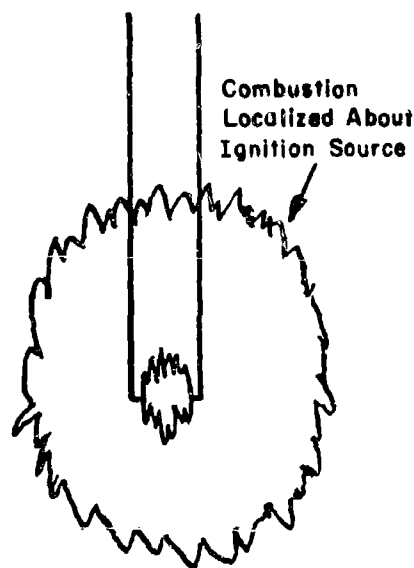
- a. Ignition Energy = E_1 ;
 $F/A = X_1 \geq X_L$,
 X_L = Standard Lean Flammability Limit



- b. Ignition Energy = $E_2 \gg E_1$;
 $F/A = X_2 < X_L$



- c. Ignition Energy = $E_3 > E_2$;
 $F/A = X_3 = X_2$



- d. Ignition Energy = $E_4 = E_2$;
 $F/A = X_4$, $X_2 < X_4 < X_L$

Figure 18. Possible Effects of Ignition Source on the Combustion of Fuel Vapors

could then support two types of combustion: (1) burning of droplets and (2) burning of the premixed vapor with the aid of energy from the burning droplets. If there are large numbers of droplets being thrown in all directions throughout the ullage, the combustion process could spread within the ullage at a rate dependent upon the collision rate of the droplets and the volume of vapor combustion about each burning droplet.

Such droplet flame spreading should occur even if there is no appreciable fuel vapor density, as long as there is appreciable droplet-droplet interaction. The addition of fuel vapor to such a droplet system could be viewed as an increase in the radius of interaction of the droplet. The droplets serve not only as droplet ignitors but also as vapor ignitors and the vapor as a droplet ignitor. As the fuel vapor concentration increases, the volume of vapor combustion around each burning droplet increases, thereby increasing the effective droplet collision rate. The flame is spread more rapidly as the fuel vapor concentration increases. The droplets, having to depend on diffusion and evaporation processes for combustion, burn too slowly to contribute greatly to the pressure rise. Their major contribution is to spread the flame and enable the vapors to burn. The vapors burn rapidly because they are already diffused with the oxygen and require only additional energy from a close proximity ignition source. The amount of droplet combustion is discussed in Appendix III.

This droplet-vapor interaction should yield an increasing pressure rise as the vapor concentration increases. This increase is due to the additional quantity of heat emitted by combusting more vapor and the reduction of heat loss because of higher reaction rate.

Figures 19 through 22 show the times to peak reaction pressure as a function of fuel temperature. As the temperature decreases from the flash point, the times increase as predicted by the droplet-vapor interaction theory. However, the times suddenly begin to decrease at a temperature about 20°F below the flash point. This decrease continues for approximately another 20°F. After this decrease, the times appear to remain constant. Apparently some physical transition took place at the region of maximum times.

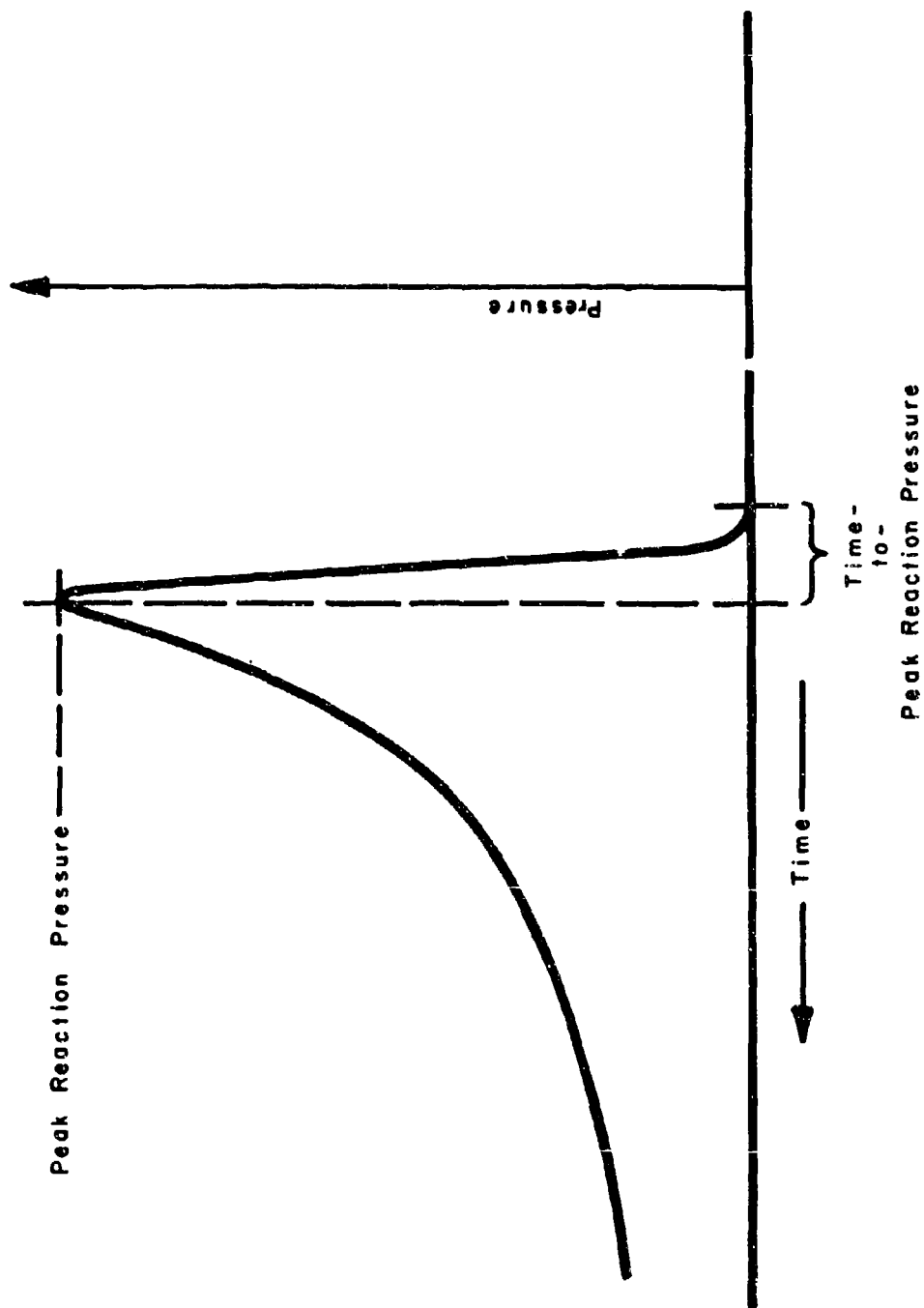


Figure 19. Time-to-Peak Reaction Pressure for a Typical Reaction Pressure Rise Pulse

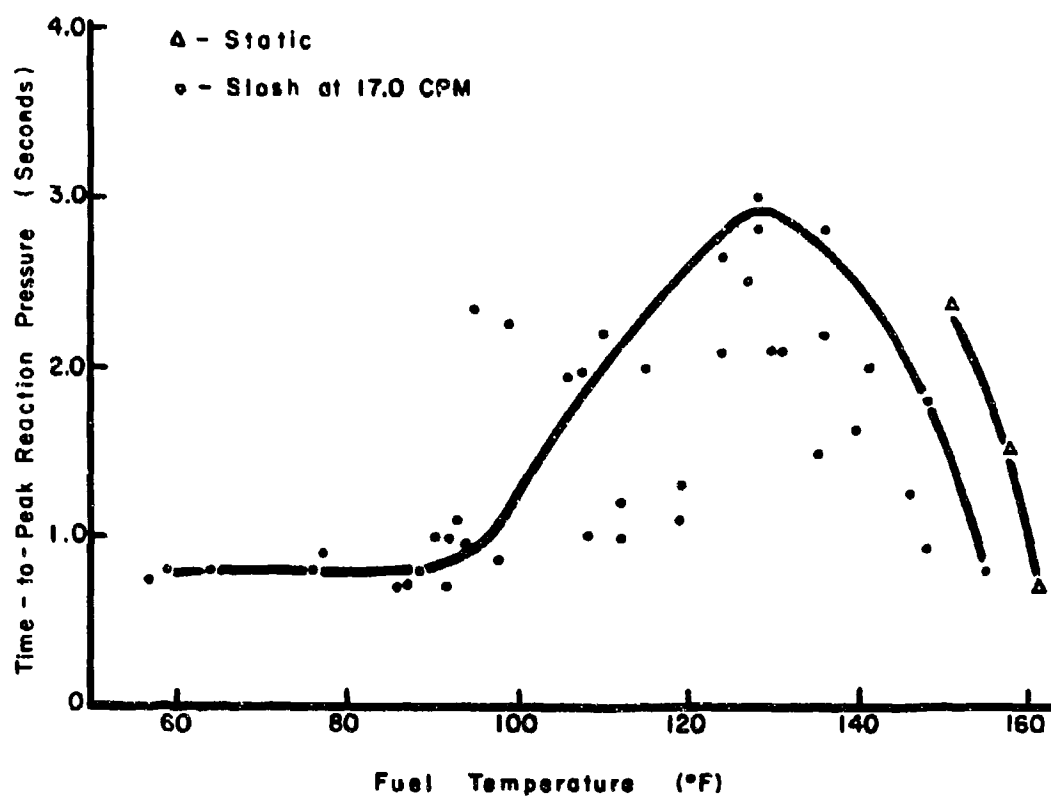


Figure 20. Times-to-Peak Reaction Pressure for JP-5 at One Atmosphere Initial Ullage Pressure

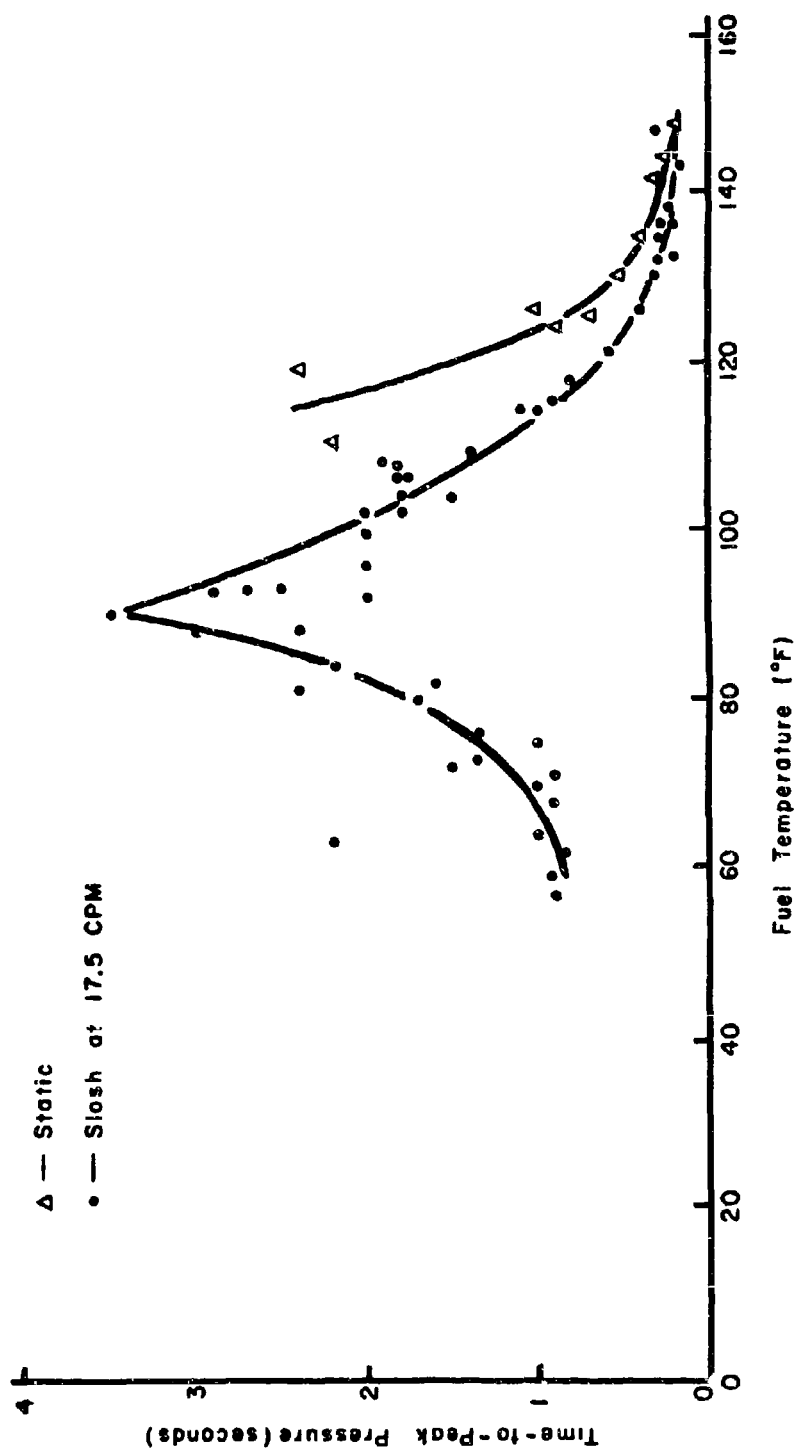


Figure 21. Times-to-Peak Reaction Pressure for JP-8 Fuel at One Atmosphere Initial Ullage Pressure

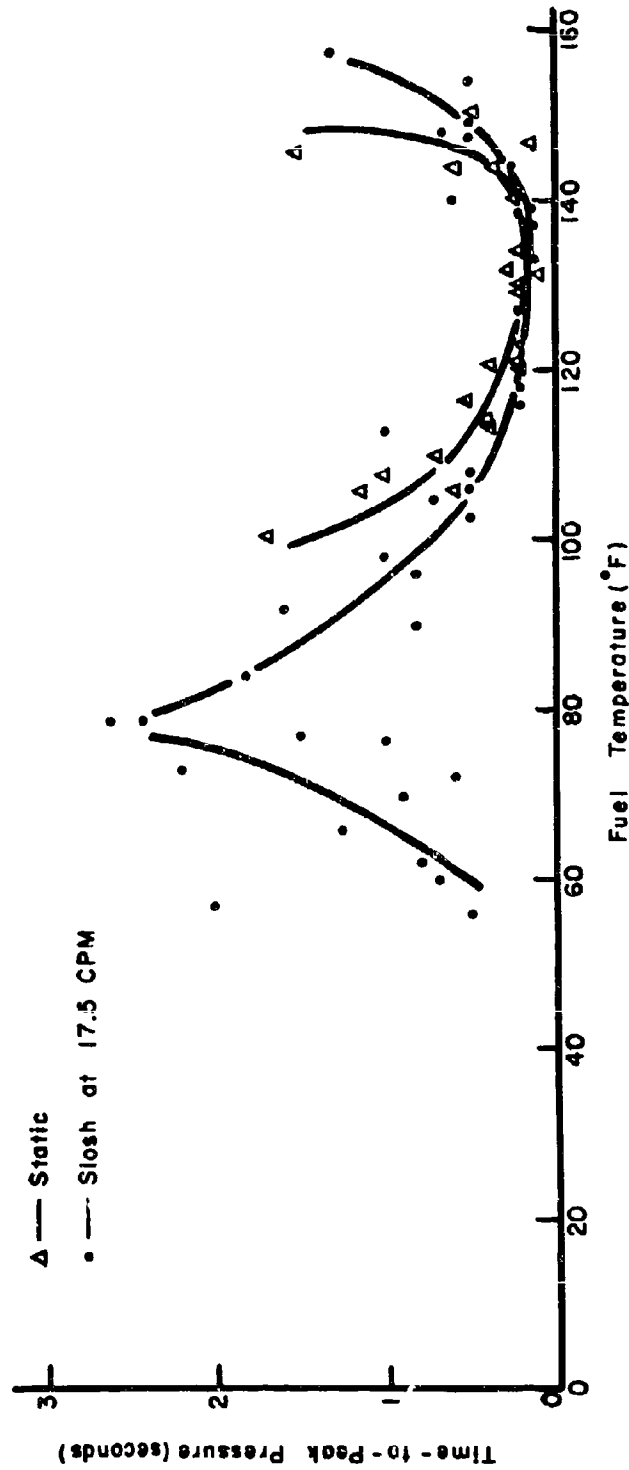


Figure 22. Times-to-Peak Reaction Pressure for JP-8 Fuel at 10 PSIA Initial Ullage Pressure

To explain this maximum time phenomenon, consider the nature and distribution of the fuel droplets generated in the test chamber. The droplets are formed by the violent splashing action caused by the sloshing motion of the chamber. The fuel splashes against the ends of the chamber and bursts into many fast moving droplets. The droplet density is greatest at the end of the chamber. Since the flame spread depends upon the overlap of droplet radii of interaction, since the radius of interaction decreases with decreasing fuel vapor density, and since density of droplet decreases as the distance from the end of the chamber increases, a temperature is reached at which the volume of combustion begins decreasing.

This temperature should correspond to the temperature of maximum time, for as the volume of flame spread decreases so should the time for spread decrease. The volume of combustion recedes to that volume in which the droplet density is great enough to allow droplet-droplet flame spread without the aid of vapor. When this minimal volume is reached, the lowering of fuel temperature has little effect because the vapor concentration is essentially negligible.

The size of this minimal combustion volume, therefore, depends upon the experimental setup. The entire ullage could have a droplet density such that every point is droplet combustible. In such a case the burning of the droplets themselves, because of their large number, could result in significant reaction pressures. Also in such a case the heat loss to the droplets would probably begin to manifest itself. A treatment of these high densities is beyond the probable realm of slosh-vibration interest.

The droplet combustion also could profoundly affect the vapor combustion in another way than flame spread. The films of lean static reactions showed a blue flame wave propagating nearly spherically outward from the ignition source. This blue flame, although emitting only low intensity visible light, was certainly the combustion process which caused the peak overpressure, because the time of peak overpressure correlated to the time of maximum extent of the wave. Oftentimes after the blue wave disappeared, bright white or orange diffusion burning followed. This latter burning did not appear to influence the pressure rise. The intensity of the blue flame appeared to decrease as the fuel-to-air ratio became leaner.

It was hoped that, by viewing the films of slosh combustion, the droplet flame spread theory could be either confirmed or refuted. However, the evidence was not clear-cut in either direction. The visible burning surrounding each droplet was much larger than the droplet itself and in most cases appeared as columns rather than spheres. The visible light surrounding each droplet was bright orange indicating that the combustion was fuel rich and was probably diffusion burning. Recalling the low intensity blue flame seen in the static case, it is highly probable that if any lean vapor combustion took place it could not be seen due to its low intensity as compared to the high intensity background of the droplet burning. However, very few, if any, of these visibly burning droplets traversed the entire length of the test vessel.

It is known that flammability ranges of gaseous fuels tend to expand with increasing temperature. Therefore, the explanation of this peculiar dependence of peak reaction pressure rise on initial fuel vapor concentration may lie in a combination of two factors. First the fuel droplets are ignited in a vapor concentration too lean to burn. The burning droplets, however, aid the vapor in the close vicinity to burn. This droplet-vapor combustion yields increasing temperature of the entire ullage. The temperature increases to a point at which the vapor alone is now flammable. The vapor then combusts throughout the rest of the ullage.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

Fuel agitation tends to lower the lean flammable temperature limit. With fuel agitation there is no distinct temperature region in which the ullage gases change from flammable to nonflammable as with the static case. Instead, there is a gradual change in the peak reaction pressures observed as the initial temperature changes. Thus any criteria for safety must consider the structural strength of the fuel tank.

In the case of fuel agitation produced by severe slosh and vibration in aircraft fuel tanks, the maximum overpressures that may result at lean vapor conditions will correlate well with the fuel vapor pressure. Thus a decrease in the vapor pressure by one half will decrease the maximum overpressure expected by approximately one half. Less severe dynamic conditions will produce less severe overpressures.

In the flammable temperature region formed by fuel agitation, there appears to be a minimum peak overpressure. In the severe slosh conditions investigated in this program, the minimum was 2-5 PSI. The minimum overpressure is probably due to the combustion of the fuel droplets generated during slosh, independent of any fuel vapor combustion. If larger amounts of droplets are produced by other means, such as fuel spray during transfer, larger overpressures will probably develop.

The rich flammable temperature limit was not affected noticeably by fuel slosh-vibration.

2. RECOMMENDATIONS

Fuel slosh and vibration in aircraft fuel tanks has been shown to be potentially hazardous. The magnitude of this hazard depends upon the amount of fuel agitation resulting from the coupling between the design of the fuel tank

and the flight conditions experienced. To make reasonably correct quantitative evaluations of the potential hazards resulting from fuel slosh and vibration as applies to specific aircraft, several areas of future investigation are indicated:

- a. Analysis of the coupling between the specific aircraft's fuel tanks and the specific flight conditions to be experienced. Fluid response within containers has been extensively investigated. The analysis of coupling between fuel tanks and flight conditions should be able to make use of present theories of fluid behavior. Therefore, this effort would primarily consist of applying these present theories to the particular fuel tanks and flight conditions.
- b. More fundamental investigation of the combustion phenomena -- Further experimentation using more sophisticated instrumentation is required to determine the nature and extent of the combustion process. Determination should be made as to whether the combustion is localized in the vicinity of the droplets or if it extends significantly into the vapor space. A quantitative correlation should be found between the amount of droplets produced and the resulting overpressure.
- c. Investigation of the effects of fuel modifications -- This effort should include testing of fuels with modified physical properties (gels and emulsions) and fuels with additives which influence flame initiation and propagation mechanisms (chemical inhibitors).
- d. Determination of the influence of fuel agitation upon gaseous inerting systems -- The effectiveness of various inerting gases such as nitrogen and carbon dioxide under dynamic conditions should be determined.
- e. Investigation of ignition source characteristics upon fuel flammabilities -- The influence of high energy ignition sources such as incendiary projectiles is of particular importance.
- f. Investigation of influence of tank internal configuration upon fuel agitation -- The influence of antislosh devices such as baffles, foams, and floats on flame ignition and propagation and reaction severity (pressure increase) should be investigated.

APPENDIX I

PROPERTIES OF JP-4, JP-5, AND JP-8 FUELS

THE AVERAGE MOLECULAR WEIGHT OF JET FUELS AS
DETERMINED BY VARIOUS METHODS FOR ESTIMATION

Sample	BP ^a	TBP-50% ^b	ASTM-50% ^c	Maxwell ^d
JP-4	123	123	125	122
JP-5	172	172	172	172
JP-8	162	164	164	163

^aBritish Petroleum Method 110.040

^bUsing the 50% point from the true boiling point curve and British Petroleum Chart 4

^cUsing the ASTM 50% thermometer reading and British Petroleum Chart 4

^dUsing Maxwell Charts 14 and 21, the ASTM slope, ASTM 50% volumetric average boiling point, and the API (American Petroleum Institute) gravity.

PENSKY-MARTENS CLOSED CUP FLASH POINTS OF
JET FUELS

Sample	Flash Point (°F)
JP-8, before use in tests	118
JP-8, after use in tests	123
JP-5, before use in tests	152
JP-5, after use in tests	155

ESTIMATED VAPOR PRESSURES OF JET FUELS

Sample Fuel	Vapor Pressure Equation	Vapor Pressure (PSI)			
		75°F	100°F	125°F	150°F
JP-4	$\log P_v = -2.28\left(\frac{1000}{\phi_R}\right) + 4.49$	1.70	2.70	3.88	5.62
JP-5	$\log P_v = -4.00\left(\frac{1000}{\phi_R}\right) + 5.76$	0.02	0.04	0.08	0.16
JP-8	$\log P_v = -3.88\left(\frac{1000}{\phi_R}\right) + 5.82$	0.04	0.08	0.16	0.29

APPENDIX II

DETERMINATION OF INFLUENCE OF ULLAGE PRESSURE UPON
PEAK REACTION PRESSURE FOR FUEL LEAN COMBUSTION

System: Gases in the ullage of a rigid fuel tank.

Assumptions:

1. Gases obey perfect gas law, $PV = nRT$
2. No heat loss
3. Heat capacities of gases are constant and equal
4. Fuel-to-air ratio is less than stoichiometric
5. Fuel vapor is completely combusted
6. System is homogeneous and at equilibrium
7. Ullage pressure is greater than vapor pressure
8. Increase in gas moles after combustion can be ignored

For a fuel temperature T_1 , we have a fuel vapor pressure of P_v . With a ullage pressure P_1 the gas mass density is ρ_1 . Letting ΔP be the reaction pressure, then

$$P_1 / T_1 = P_f / T_f = (P_1 + \Delta P) / (T_1 + \Delta T) \quad (1)$$

where T_f = final system temperature

P_f = final system pressure

ΔT = reaction temperature rise

Solving Equation 1 for ΔP yields

$$\Delta P = P_1 \Delta T / T_1 \quad (2)$$

The reaction temperature rise can be equal to the heat released during combustion divided by the heat capacity times the system mass. Thus

$$\Delta T = Q / (M_1 C_1)$$

where Q = heat released

M_1 = system mass

C_1 = system heat capacity

The heat released will be proportional to the amount of fuel, the amount of fuel is proportional to the fuel vapor pressure, the system mass is proportional to the mass density, the mass density is proportional to the system pressure, and the system heat capacity is constant, so that

$$\Delta T \propto P_v / P_1 \quad (3)$$

substituting ΔT from Equation 3 into Equation 2 yields

$$\begin{aligned} \Delta P &= P_1 \Delta T / T_1 \propto (P_v / P_1) / (T_1 / P_1) \\ \Delta P &\propto P_v / T_1 \end{aligned} \quad (4)$$

Thus the reaction pressure is not a function of the ullage pressure if the assumptions are valid.

1. EFFECT OF CHANGE IN SPECIFIC HEAT

The various component gases have different heat capacities so that the initial heat capacity of the system may be written

$$C_1^i = \alpha P_v C_F + \beta P_a C_a$$

where α and β are constants which convert pressure into masses, subscript a refers to air, and subscript F refers to fuel.

The final system heat capacity may be written as

$$C_1^f = \beta P_a C_a + \gamma P_p C_p$$

where γ serves similarly as α and β and subscript p refers to the combustion products.

In dealing with lean reactions, $P_v / P_1 \cong 0.01$, so that the heat capacity of the air far outweighs the heat capacity of the fuel or the products and can be used as the heat capacity of the system.

Heat capacities are not constant with temperature or pressure so modification of results is in order. We have seen that the ΔP was not a function of the ullage pressure because, as the ullage pressure was reduced, the reaction temperature increased due to the reduction of mass being heated. The heat capacity of air increases as the system temperature increases so that, in the case of constant heat input as concerns us here, a reduction in initial system pressure reduces the system mass thereby increasing the final system temperature and heat capacity which results in a lower ΔP .

To gain an idea of the magnitude of this effect of increased heat capacity, consider the following:

$$T = 318^\circ K$$

Let ΔP at atmospheric ullage pressure = 60 PSI. Thus

$$\Delta P = P_1 \Delta T / T_1 \Rightarrow \Delta T = T_1 \Delta P / P$$

$$\Delta T = 318 (60 / 14.7) = 1300^\circ K$$

and

$$T_f = 318 + 1300 = 1618^\circ K$$

with

$$C_1^f \cong 0.199 \frac{\text{cal}}{\text{gm}^\circ K}$$

Now let $P_1 = 10$ PSIA. Thus

$$\Delta T_{\text{atm}} / \Delta T_{10} = 10 / 14.7$$

$$\Delta T_{10} = 14.7 (1300 / 10) = 1910^\circ K$$

and

$$T_{f,10} = 318 + 1910 = 2228^\circ K$$

with

$$C_1^f \cong 0.222 \frac{\text{cal}}{\text{gm}^\circ K}$$

Comparing

$$\begin{aligned}\Delta P_{atm} / \Delta P_{10} &\cong C_{1,10}^f / C_{1,atm}^f \\ 60 / \Delta P_{10} &\cong 0.222 / 0.199 \\ \Delta P_{10} &\cong 54 \text{ PSI}\end{aligned}$$

2. EFFECT OF HEAT LOSS

We have seen that a lower initial system pressure results in a higher final system temperature assuming that the same quantity of fuel is combusted. This higher temperature will mean that the heat loss rate is increased. Thus the ΔP for lower ullage pressures would be even further reduced. The increased heat loss rate is due to two factors: the increased temperature differential and the increased thermal conductivity of the gas accompanying the increased temperatures.

In considering the heat loss, we must also consider the time allowed for heat loss. A chemical reaction which takes place more rapidly has less time to lose heat before it reaches peak pressure. When the initial system pressure is reduced, the chemical reaction is pushed closer to the stoichiometric region. The closer a reaction is to being stoichiometric, the more rapid is the reaction rate. One might assume that the time-to-peak-reaction pressure is an indicator of the reaction rate. Then from Figures 21 and 22, we see that, for static reactions at 120°F, $\Delta t = 1.4$ seconds for one atmosphere initial ullage pressure and $\Delta t = 0.3$ second for 10 PSIA initial ullage pressure. The reaction rate at the more nearly stoichiometric condition (10 PSIA) is more than four times as fast as the lean reaction rate. Thus the increase in heat loss rate may be more than compensated for by the increase in reaction rate.

APPENDIX III

DROPLET COMBUSTION

Comparison of reaction pressure data with vapor pressure data indicates (1) the reaction pressure becomes very small in the temperature region in which the vapor pressure becomes very small relative to the vapor pressure at the flash point; (2) the increase in reaction pressure follows approximately the increase in vapor pressure up to the near stoichiometric region; and (3) if the vapor pressure is plotted simultaneously with the reaction pressure for a scale such that the flash point reaction pressure and the flash point vapor pressure are coincident, the vapor pressure curve is above the reaction pressure for temperatures above the flash point and the reaction pressure slightly exceeds the vapor pressure below the flash point, but again is surpassed by the vapor pressure at still lower temperatures. From these observations, the vapor present at the time of ignition appears to be the controlling parameter in the ensuing reaction. However the deviation between the reaction pressure curve and the vapor pressure curve suggests the superposition of another reaction to the vapor reaction.

Two courses are open to explain this deviation: (1) there is a decrease in the vapor reaction at the upper and lower ends of the lean region or (2) there is an addition to the vapor reaction at the middle region. If there were a lessening of the vapor reaction, one would think that its magnitude would be consistently increasing or decreasing over the lean region. Such a reaction would not modify the vapor reaction in a manner consistent with the data. Therefore, the most favorable candidate is the second course, i.e. finding a reaction which has a maximum in the middle region.

Consider the evaporation and combustion of the fuel droplets dispersed throughout the ullage. Combustion of droplets would add heat and therefore increase the reaction pressure. However, unless these droplets are very small (less than 10 microns diameter), they will have to evaporate before burning. The amount of fuel droplets evaporated will depend upon the rate at which heat is absorbed by the droplets and the time in which the evaporation heat is applied.

The rate of evaporation will depend upon the characteristics of the fuel, the surface area involved, and the temperature differential. If we assume that the thermal conductivity and surface area are constant, the rate is proportional to the temperature differential. The reaction pressure also depends upon the temperature differential, so that the rate of evaporation can be expressed as proportional to the reaction pressure.

The length of time that the temperature differential is applied to the droplet is roughly proportional to the time from the beginning of the combustion to the peak pressure rise. The amount of fuel evaporated is then proportional to the reaction pressure and the time-to-peak reaction pressure.

The magnitude of the droplet combustion contribution must be determined empirically. Figure 23 shows the times-to-peak reaction pressure and the fuel vapor pressure (which is proportional to the peak reaction pressure). If these two plots are taken as representative of the times and temperature differentials to be used in calculating the droplet contribution, Figure 24 then shows the droplet contribution temperature profile. Choosing the magnitude of the peak droplet contribution to be 2.5 PSI and adding this contribution to the vapor contribution (64 PSI at 120°F) give the corrected reaction pressure profile shown in Figure 25.

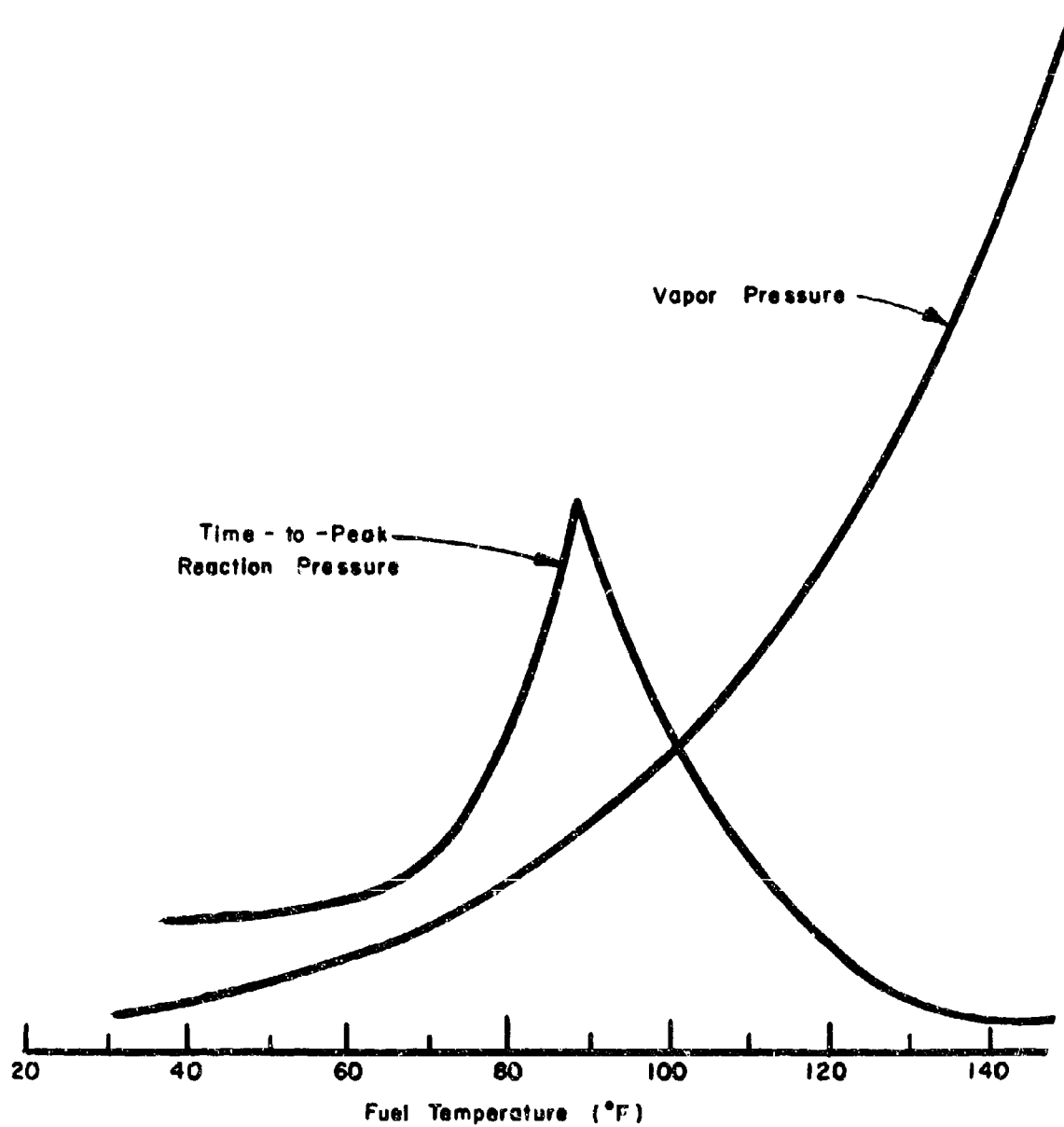


Figure 23. Time-to-Peak Reaction Pressure and Vapor Pressure for JP-8 at One Atmosphere Initial Ullage Pressure

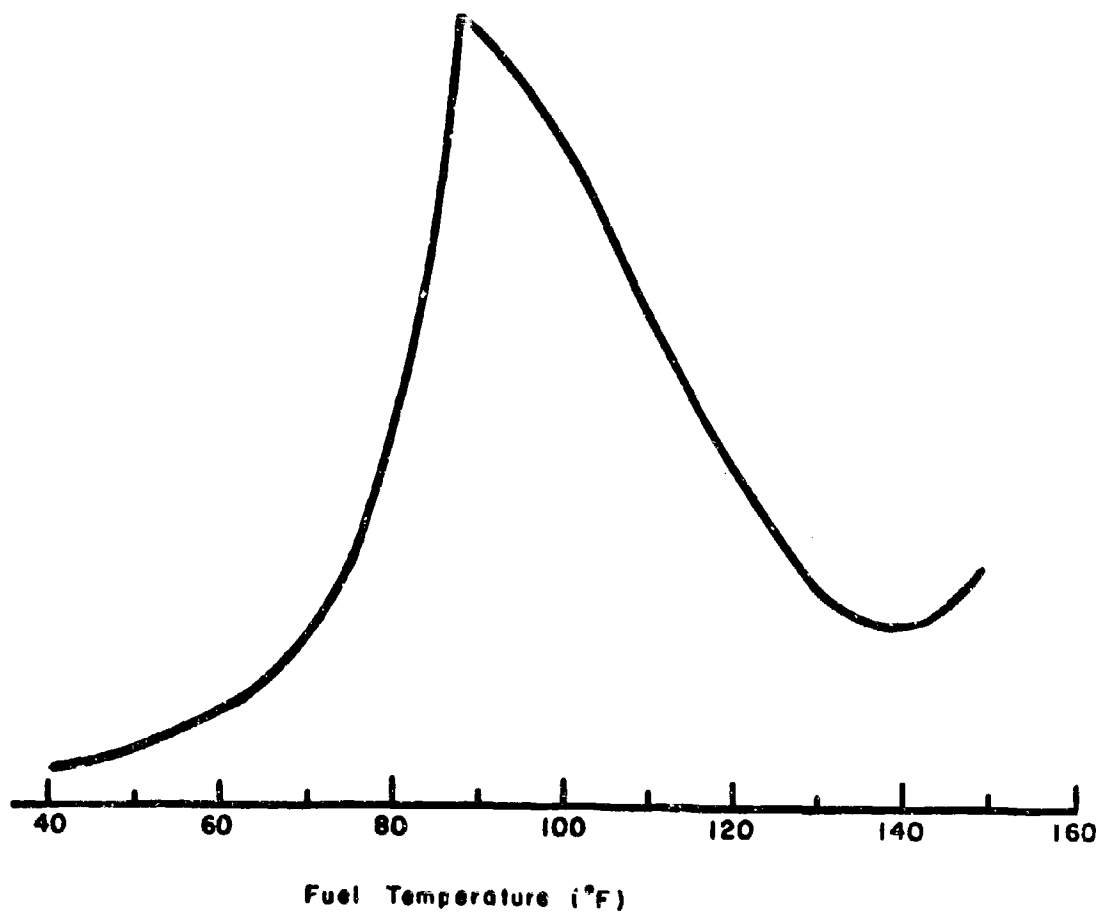


Figure 24. Droplet Combustion Contribution ($\Delta t \times P_v$) for JP-8 at One Atmosphere Initial Ullage Pressure

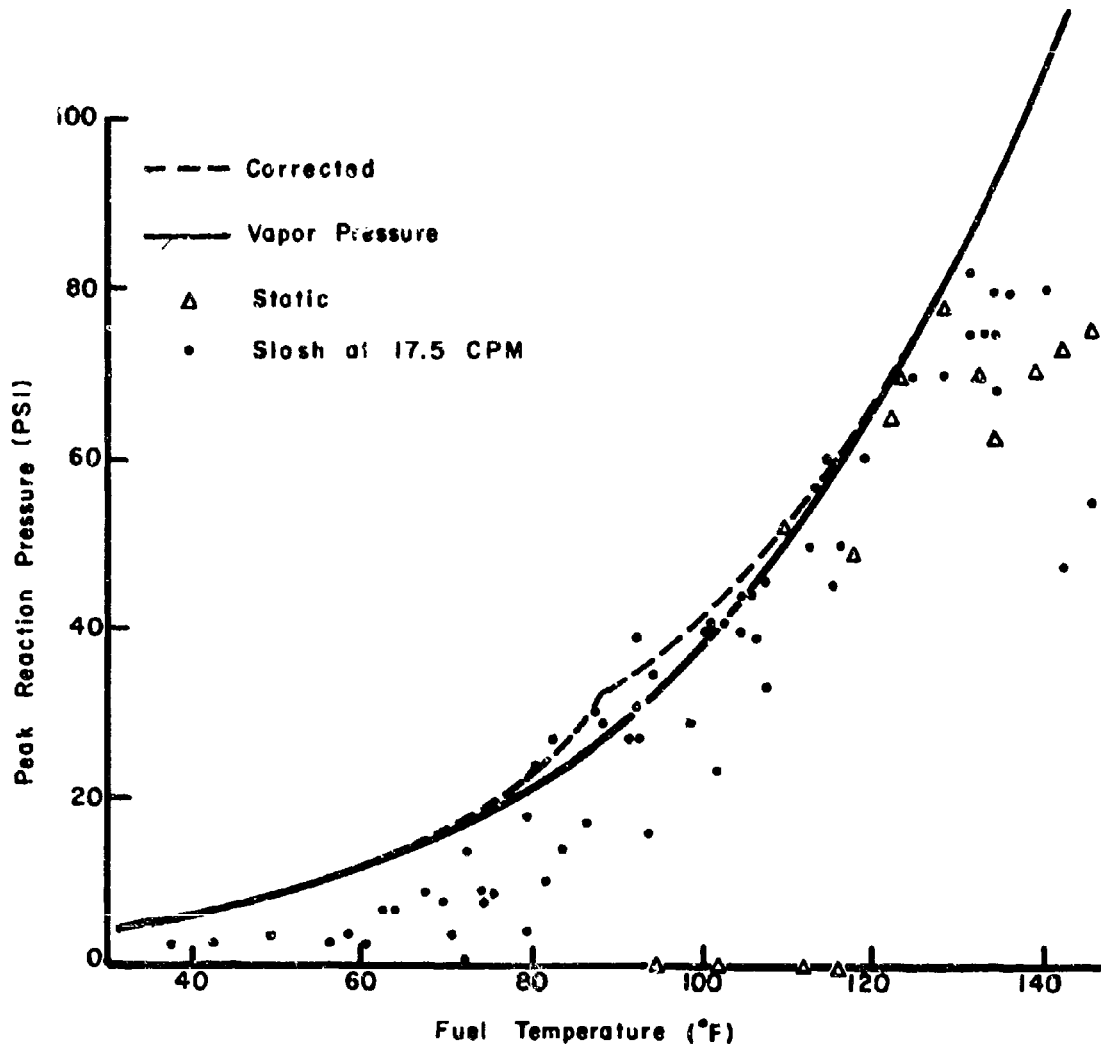


Figure 25. Correction of Droplet Combustion Pressure Rise to the Vapor Combustion Pressure Rise for JP-8 at One Atmosphere Initial Ullage Pressure

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE EFFECTS OF FUEL SLOSH AND VIBRATION ON THE FLAMMABILITY HAZARDS OF HYDROCARBON TURBINE FUELS WITHIN AIRCRAFT FUEL TANKS			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
5. AUTHOR(S) (First name, middle initial, last name) Edwin E. Ott, Captain, USAF			
6. REPORT DATE November 1970		7a. TOTAL NO. OF PAGES 61	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO.		9a. ORIGINATOR'S REPORT NUMBER(S) AFAPL-TR-70-65	
b. PROJECT NO. 3048			
c. Task No. 304807		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433	
13. ABSTRACT This report deals with the effects of liquid fuel motion on the flammability of hydrocarbon turbine fuels in aircraft fuel tanks. Three military turbine fuels, JP-4, JP-5, and JP-8, were used in the testing. The fuels were placed in an explosionproof cylindrical test vessel (80-gallon capacity) and subjected to slosh and vibration. An electric arc was formed within the ullage which ignited any flammable fuel-air mixture present. The pressure rise from combustion was measured and correlated with initial conditions. The major effect of fuel slosh and vibration was to lower or abolish the lean flammable temperature limit of the fuel. The rich flammable temperature limit was unchanged. An analysis was performed on these results and an explanation proposed based upon the hypothesis that all the fuel vapor in the ullage burns for combustion below the flash point.			

DD FORM 1473
1 NOV 65

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14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Aviation Fuels - JP-4, JP-5, and JP-8						
	Flammability Limits						
	Fuel Mists						
	Aircraft Safety						
	Slosh						
	Vibration						

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